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Dust Abundance and Properties in the Nearby Dwarf Galaxies NGC 147 and NGC 185

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ABSTRACT

We present new mid- to far-infrared images of the two dwarf compact elliptical galaxies that are satellites of M31, NGC 185 and NGC 147, obtained with the Spitzer Space Telescope. Spitzer's high sensitivity and spatial resolution enable us for the first time to look directly into the detailed spatial structure and properties of the dust in these systems. The images of NGC 185 at 8 and 24 micron display a mixed morphology characterized by a shell-like diffuse emission region surrounding a central concentration of more intense infrared emission. The lower resolution images at longer wavelengths show the same spatial distribution within the central 50'' but beyond this radius, the 160 μ m emission is more extended than that at 24 and 70 μ m. On the other hand, the dwarf galaxy NGC 147 located only a small distance away from NGC 185 shows no significant infrared emission beyond 24 micron and therefore its diffuse infrared emission is mainly stellar in origin. For NGC 185, the derived dust mass based on the best fit to the spectral energy distribution is $1.9 \times 10^3 M_\odot$, implying a gas mass of $3.0 \times 10^5 M_\odot$. These values are in agreement with those previously estimated from infrared as well as CO and HI observations and are consistent with the predicted mass return from dying stars based on the last burst of star formation 1×10^9 yr ago. Based on the 70 to 160 μ m flux density ratio, we estimate a temperature for the dust of ~ 17 K. For NGC 147, we obtain an upper limit for the dust mass of $4.5 \times 10^2 M_\odot$ at 160 μ m (assuming a temperature of ~ 20 K), a value consistent with the previous upper limit derived using ISO observations of this galaxy. In the case of NGC 185, we also present full 5 – 38 μ m low-resolution

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($R \sim 100$) spectra of the main emission regions. The IRS spectra of NGC 185 show strong Polycyclic Aromatic Hydrocarbons (PAH) emission, deep silicate absorption features and H_2 pure rotational line ratios consistent with having the dust and molecular gas inside the dust cloud being impinged by the far-ultraviolet radiation field of a relatively young stellar population. Therefore, based on its infrared spectral properties, NGC 185 shows signatures of recent star formation (a few $\times 10^8$ years ago), although its current star formation rate is quite low.

Subject headings: galaxies: dwarf — galaxies: individual (NGC 147 and NGC 185)
— galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction
— ISM: structure

1. Introduction

It was by resolving into stars the two dwarf elliptical galaxies NGC 147 and NGC 185, along with their formidable large companion the Andromeda galaxy, that Baade refined his concept of two stellar populations in the 1940s. Of NGC 147, Baade (1944) wrote “In contrast with the uncertain information provided by the blue-sensitive plates, the 4-hour red exposure of NGC 147 is truly revealing. It shows that the nebula is a large star cloud, ellipsoidal in structure, and of a density gradient so low that even the central region is fully resolved”. He later on remarked that NGC 147 is an example of a dust-free galaxy containing only stars of Population II (Baade 1951). As part of the same work, Baade’s notes on NGC 185 revealed “NGC 185, considerably brighter than NGC 147, has been classified by Hubble as Ep, the peculiarity being the abnormally slow increase in intensity toward the center. It is intermediate in this respect to NGC 205, similarly classified by Hubble as Ep, and NGC 147. NGC 185 is one of the few elliptical nebulae in which patches of obscuring material are conspicuous. Two such dark clouds are near the center of NGC 185”. Based on his observation of bright young blue stars in NGC 185, he also noted the apparent relationship between these Population I (metal-rich) stars and the presence of dust.

Based on our current understanding of stellar evolution, we now know that it is the dying stars that inject gas and metal-enriched dust back into the interstellar medium (ISM) (Faber & Gallagher 1976). The presence of planetary nebulae in NGC 185 (Ford, Jenner & Epps 1973), for example, confirms that mass loss is occurring in this dwarf elliptical galaxy. From this enriched material is formed a new population of luminous hot and young metal-rich stars. Indeed, the ISM in NGC 185, as seen in the form of atomic (HI) and molecular gas (CO), appears spatially concentrated near the present-day star-forming region (Young 2001; Welch, Mitchell & Yi 1996). However, whereas NGC 185 contains gas, dust and young

stars with ages of about 100 Myr (in the central 150 pc by 90 pc region; Martinez-Delgado, Aparicio, & Gallart 1999) to 400 Myr (Butler & Martinez-Delgado 2005), it is unknown why NGC 147 appears to be presently dust- and gas-free (Young & Lo 1997; Sage, Welch, & Mitchell 1998) and had its most recent star forming episode $\lesssim 1$ Gyr ago (Han et al. 1997). Either an efficient removal mechanism of some kind is at play (external sweeping, formation of condensed objects, gas ejection by violent nuclear activity, or sweeping by a hot galactic wind) or NGC 147 is at a completely different evolutionary stage than NGC 185. Although there are some claims that these two dwarf galaxies form a stable binary system (van den Bergh 1998), the latter explanation implies that these two galaxies did not form at the same time and/or in the same environment despite their physical proximity.

In this paper, we explore the nature of these two systems from a completely new direction, using a different wavelength regime. We present new mid- to far-infrared images of NGC 147 and NGC 185 obtained with the *Spitzer Space Telescope* (hereafter *Spitzer*). The higher sensitivity and spatial resolution of *Spitzer* over previous infrared observatories enable us for the first time to measure *directly* the detailed structure and composition of the dust in these two dwarf galaxies. The paper is organized as follows. In Section 2, we describe the *Spitzer* observations and the data reduction. The *Spitzer* images are presented in Section 2, followed by a description of the mid- and far-infrared emission morphology and a comparison with other tracers of the ISM in Section 3. Foreground point source contamination is discussed in Section 4. Dust mass measurements and gas mass estimates are derived in Section 6 based on the spectral energy distribution of the dwarf galaxies presented in Section 5. In Section 7, we present the results of the analysis of the first set of *Spitzer* spectroscopic observations of one of M31’s dwarf galaxies. We discuss the spectral line measurements and spectral properties of NGC 185’s dust clouds. We conclude our paper by presenting a summary of our observations and results in Section 8.

2. Observations and Data Reduction

2.1. IRAC and MIPS Images

The mid-infrared imaging observations of the two dwarf galaxies NGC 147 and NGC 185, shown in the optical in Figure 1, were obtained with IRAC, the infrared camera (Fazio et al. 2004) on board *Spitzer* (Werner et al. 2004) on 2005 July 25 and 2005 August 20, respectively, as part of the GO2 program to study in detail the dust in M31’s four elliptical companions (PI: Marleau, Program ID: 20173). A region 5’ in size was mapped in each of the four IRAC channels using a total integration time of 84 seconds per sky position. The 24, 70 and 160 μ m MIPS (the Multiband Imaging Photometer for *Spitzer*; Rieke et al. 2004)

photometric observations of both galaxies were completed on 2006 February 16 (24 & 70 μ m) and on 2005 September 04 (160 μ m) with an integration time per pixel of 606, 440 and 63 seconds, respectively.

The images obtained with channels 1 and 2 (at 3.6 and 4.5 μ m) were used mostly to determine the stellar contribution to the overall spectral energy distribution of the galaxy. Channels 3 and 4 (at 5.8 and 8 μ m) contain the most information about the dust properties; channel 4 in particular, with a passband centered at 7.9 μ m includes some of the strongest Polycyclic Aromatic Hydrocarbons (PAH) emission features known (e.g. bands at 7.7 and 8.6 μ m); these are considered some of the best tracers of very small particles (see e.g. Li & Draine 2001, Draine & Li 2001 and references therein).

The IRAC Basic Calibrated Data (BCD) produced by the SSC pipeline version S14.0.0 (2006 May) were combined with the SSC MOPEX software to produce final mosaics with pixel size 1.2'' (all channels) and spatial resolutions of less than 2'' FWHM. The MIPS BCDs used in this paper were generated with the SSC pipeline version S13.2.0 (2005 November - 2006 January). These versions of the SSC software are quite stable and adequate for processing NGC185 and NGC147 since the brightness of both systems is outside the regime affected by non-linearity, latencies or muxbleed effects.

The MIPS 24 μ m data suffer from the “First-frame Effect,” where the first, and often the second and third, frame of every commanded sequence of observations have a shorter exposure time and are depressed in response by as much as 10 – 15%. Therefore, based on the MIPS IST recommendation, the first two BCD frames of every commanded sequence of observations were discarded. Sometimes the pipeline flat-fielding does not completely remove background gradient across the MIPS 24 μ m frames. Therefore, we performed an extra flat-fielding of our BCDs by “self-calibrating” each BCD, i.e. flattening (dividing) each BCD by the normalized median BCD image. As the dither positions between BCD images have the emission from the galaxy overlapping, the galaxy was masked before the median was calculated. We created our own median by masking the galaxy and replacing the masked pixels by the median of the non-masked pixels in each BCD image. Further processing of the BCDs consisted of removing the zodiacal light component of each frame by subtracting the estimate taken from the header keyword ZODY_EST (the median value across the stack of BCDs was 24.17 MJy/sr for NGC 147 and 24.36 MJy/sr for NGC 185). To perform background correction of our BCDs we used “overlap.pl” in MOPEX. This levels the backgrounds to ensure that the final mosaic is not “patchy”. Finally, once all these corrections were applied, the processed BCDs were re-mosaicked using “mosaic.pl” in MOPEX.

The MIPS 70 μ m data contain the “stim” BCD frames. Therefore, these stim BCD

images were removed from the stack of BCDs. In total, 90 BCDs were removed out of the 468 BCD frames for each galaxy (leaving 378 BCD frames each). Also, variation across columns are seen at $70\mu\text{m}$ due to readout. These variations were removed by subtracting the median of the values along each column for every BCD (masking the NaNs and the galaxy), a procedure referred to as “column filtering”. A median value of the whole image (of pixels that were not masked, i.e. NaNs or belonging to the galaxy) was added back to retain the background flux value. As for MIPS $24\mu\text{m}$, further processing of the BCDs consisted of removing the zodiacal light component of each frame by subtracting the estimate taken from the header keyword ZODY_EST (the median value across the stack of BCDs was 6.07 MJy/sr for NGC 147 and 6.14 MJy/sr for NGC 185). Given that the coverage of the final mosaic is non-uniform (lower coverage regions in the bottom left of the galaxy), we performed a background correction of our BCDs by using “overlap.pl” in MOPEX. Finally, once all these corrections were applied, the processed BCDs were re-mosaicked using “mosaic.pl” in MOPEX.

As for the MIPS $70\mu\text{m}$ data, the MIPS $160\mu\text{m}$ data contain as well the “stim” BCD frames. Therefore, these stim BCD images were also removed from the stack of BCDs. In total, 72 BCDs were removed out of the 468 BCD frames for each galaxy (leaving 396 BCD frames each). Further processing of the BCDs consisted of removing the zodiacal light component of each frame by subtracting the estimate taken from the header keyword ZODY_EST (the median value across the stack of BCDs was 0.93 MJy/sr for NGC 147 and 0.94 MJy/sr for NGC 185). No overlap correction was applied since the array is small and has a gap. Finally, once all these corrections were applied, the processed BCDs were re-mosaicked using “mosaic.pl” in MOPEX.

The final 24, 70 and $160\mu\text{m}$ mosaics were produced with square pixels, 1.225, 4.0 and $8.0''$ in size and had a final spatial resolution of 6, 18 and $40''$ FWHM, respectively (Rieke et al. 2004). The astrometry was checked by comparing 2MASS point sources on IRAC $8\mu\text{m}$ images and then comparing the $8\mu\text{m}$ point sources with $24\mu\text{m}$. The astrometry was found accurate to within the astrometric accuracy of 2MASS ($0.2''$) and no correction was applied. The final IRAC and MIPS mosaics of NGC 147 and NGC 185 are shown in Figure 2 & 3 and 4 & 5, respectively.

2.2. IRS Spectra

Observations of NGC 185 at three different dust cloud location visible in the optical image of the galaxy were performed using the Infrared Spectrograph (IRS; Houck et al. 2004) on board *Spitzer* on 2006 January 29-30 (see Table 1 and Figure 6). In addition, a

separate observation of the sky (see Table 1, “NGC185IRSSky”), located 6′ away from the center of NGC 185, was obtained for accurate background subtraction. All four modules, Short-Low 2 (SL2; $5.2 - 8.7\mu\text{m}$) and 1 (SL1; $7.4 - 14.5\mu\text{m}$), Long-Low 2 (LL2; $14.0 - 21.3\mu\text{m}$) and 1 (LL1; $19.5 - 38.0\mu\text{m}$), were used, to obtain full $5 - 35\mu\text{m}$ low-resolution ($R \sim 100$) spectra. There were two nodding positions per observation and a number of 10(SL)/20(LL) cycles of 60(SL)/30(LL) seconds ramp duration were used at each nod position giving a total on-source integration time of 1219 (SL) and 1258 (LL) seconds per pixel.

The IRS data used in this paper were generated by the SSC pipeline version S13.2.0 (2006 January). The data reduction consisted of the following steps. First, the four nod positions of the sky observations in each channel were combined (by computing the median value) to create a “super sky”. The uncertainty image associated with the super sky was also created. Second, the sky was subtracted from each “_coa2d.fits” spectral image of the dust clouds. The uncertainty images associated with the background subtracted image was also computed. Third, we used the IDL interactive tool IRSCLEAN_MASK¹ to create a mask of rogue pixels associated with the background subtracted spectral images and to clean those images prior to spectral extraction. Finally, spectral extraction was done using the Spitzer IRS Custom Extraction software SPICE² using the “extended source with regular extraction” template. The first step of the extraction was done using the module called “profile” which computes and plots the mean spatial flux profile. The second step was done using the module called “ridge” which finds the peak in the spatial profile. For this step, we selected the option “manual” to ensure that the extraction was always done at the same location and for the same source (since sometimes there were more than one peak) at the two nod positions. The extraction was done with the “extract” module. For this, we did not use the full width extraction (default 28 pixels) but we specified an extraction of width 7 pixels. This is because the full width extraction introduces spurious lines at the very edge of the extraction width where the spectral image is not as clean and the narrower extraction also produces a better signal-to-noise spectrum. The extraction spectra were flux calibrated using the module called “tune” which produces two output spectra, “aploss_spect.tbl” and “extsrc.tbl”. The former is the spectrum derived assuming a point source extracted with the full aperture and the latter is the spectrum “aploss_spect.tbl” multiplied by the slit loss correction. The slit loss correction assumes that at a given wavelength the source is infinite in extent and has a constant surface brightness. As we did not use a full width extraction, we did our own flux calibration of the “extsrc.tbl” spectra (see below). The spectral extraction procedure using SPICE is illustrated in Figure 7. After extraction was

¹http://ssc.spitzer.caltech.edu/archanalyst/contributed/irsclean/IRSCLEAN_MASK.html

²<http://ssc.spitzer.caltech.edu/postbcd/spice.html>

performed, we averaged together the spectra at the two nod positions for each of the SL2, SL1, LL2 and LL1 wavelength coverage and trimmed the noisy edges.

The 1st and 2nd order of the SL and LL spectra were found to be in good agreement. However, this procedure left a mismatch between the SL and the LL regions of the spectra. We therefore scaled the SL to match the LL (using a multiplicative factor; IRS Data Handbook Version 3.1, 2007). To properly flux calibrate our spectra, as we did not use a full width extraction, we used our flux density measurements obtained from the $24\mu\text{m}$ images. As our extraction width remained exactly the same for all IRS target positions, we extracted the photometry for “NGC185IRSNorth” (brightest cloud) and applied the same additive offset to the other two spectra, keeping their relative brightness the same. The aperture for the photometry was selected to be centered on the target position for “NGC185IRSNorth”, with an area of $0.106''^2$, matching the IRS extraction area: the slit width ($10.7''$) multiplied by the width of extraction ($7 \text{ pix} \times 5.1''/\text{pix} = 35.7''$). For “NGC185IRSNorth”, after background subtraction, we obtained a flux density measurement of $3.8 \pm 0.4 \text{ mJy}$. The “NGC185IRSNorth” spectrum was therefore flux calibrated using this measurement and the other spectra were offset accordingly.

3. Morphology of Infrared Emission

3.1. NGC 147

Figure 8 displays a three-color image, as seen by IRAC at 3.6 , 5.8 and $8\mu\text{m}$, of NGC 147. At the depth of our observations, we are unable to detect significant dust emission beyond $24\mu\text{m}$. There is a small contribution at shorter wavelength (at 24 , 8 and $5.8\mu\text{m}$), however, the dominant emission at these wavelengths, as seen in Figure 8, is stellar in origin. The stellar emission extends to about $4.2'$ (823 pc) along the major axis of the galaxy and $2.2'$ (431 pc) along the minor axis. At a distance of $675 \pm 27 \text{ kpc}$ (McConnachie et al. 2005), $1.0'$ corresponds to 196 pc . The two prominent extended sources easily detected at $70\mu\text{m}$ (Figure 3) can be easily identified as background galaxies based on their morphology and color (see Figure 8).

The lack of significant dust emission in this galaxy is consistent with observations done at 20 cm with the Very Large Array (VLA; Young & Lo 1997) looking for HI emission and at 115 GHz with the NRAO 12 m telescope at Kitt Peak (Sage, Welch, & Mitchell 1998) searching for the CO J=1-0 line emission. Both HI and CO remain undetected in this galaxy.

3.2. NGC 185

Figure 9 displays an IRAC three-color image of NGC 185 where the dust clouds at 5.8 and $8\mu\text{m}$ stand out within the stellar background detected by the shorter wavelength bands.

As seen from these images, especially the highest resolution image available at $8\mu\text{m}$, the diffuse dust emission from NGC 185 has a mixed morphology characterized by a shell-like emission region extending from the south to the east of the galaxy center surrounding a central region of more concentrated emission. The mechanism responsible for such a morphology is not known but, as can be inferred from Figure 9, it is likely the result of the recent star forming activity detected in this galaxy. The morphology of the dust emission at longer wavelengths is similar to that seen at shorter wavelengths in the central region. Even at $70\mu\text{m}$, where the spatial resolution is $18''$ FWHM, we can still distinguish the shell-like structure and central emission region. At $160\mu\text{m}$ ($40''$ FWHM), the spatial structure of the emission is unresolved.

The peak of the emission is concentrated at the center in a region $\sim 30''$ in diameter. At the adopted distance of 616 ± 26 kpc (McConnachie et al. 2005), $1.0'$ corresponds to 179 pc. Therefore, an angular size of $30''$ corresponds to a physical size of 89 pc. However, the diffuse dust emission is clearly seen to extend to a much larger distance, covering a region approximately $2.5'$ diameter in size (or 447 pc).

The ISM in NGC 185 is concentrated near the present-day star-forming region, although the atomic and molecular components are not spatially coincident (CO, Welch, Mitchell & Yi 1996; HI, Young 2001). As shown in Figure 10, the location of the main peak of each of the CO and HI emission does not match exactly the location of the peak of the dust emission, although they both are coming from the same dust cloud (“NGC185North”, see Table 4 and Figure 16). The morphology and kinematic properties of the ISM are consistent with it originating from stars internal to NGC 185 (Young & Lo 1997; Martinez-Delgado, Aparicio & Gallart 1999).

Figure 11 shows the MIPS three-color image of NGC 185. In order to understand the distribution of the cold dust in NGC 185 as traced by the $160\mu\text{m}$ light, we have performed some radial cuts along the dust clouds symmetry axis and compared them with the 24 and $70\mu\text{m}$ emission that trace other dust temperature and size (small grains) components. This comparison requires that we match the 24 and $70\mu\text{m}$ beams to that of the $160\mu\text{m}$ array (FWHM $\sim 40''$). To accomplish this, we convolved the 24 and $70\mu\text{m}$ images with their corresponding kernels selecting a PSF representative of 100 K black body emission (see e.g. Gordon et al. 2008). Figure 12 shows one of the surface brightness cuts (at a position angle of 52° , i.e. along the major-axis of the infrared diffuse emission) normalized and shifted so

that the three bands start with a common baseline near zero. The radial distribution of the three MIPS bands is similar within the central $50''$ but beyond this radius, the $160\mu\text{m}$ emission is more extended than that at 24 and $70\mu\text{m}$, a trend observed in other galactic systems (e.g. Engelbracht et al. 2004; Hinz et al. 2006).

4. Resolved Stars and Foreground Contamination

Point sources were extracted in the central $5' \times 5'$ region of both dwarf galaxies in the 5.8, 8.0 and $24\mu\text{m}$ images using the source extraction software StarFinder (Diolaiti et al. 2000). *Spitzer* $[8] - [24]$ and $[5.8] - [8]$ colors were derived for these point sources and compared to the colors of a sample of Galactic AGB and K Giant star templates in the mid-infrared observed with the Short Wavelength Spectrometer (SWS, covering a wavelength range of $2.4 - 45.2\mu\text{m}$) on board of the Infrared Space Observatory (ISO) in order to identify the type of resolved stars present in NGC 147 and NGC 185 and to estimate the amount of foreground contamination from our Galaxy in their direction (the contamination from M31 is considered negligible at this large distance from their large companion). For each galaxy, we detected 34 point sources with emission in all of the 5.8, 8 and $24\mu\text{m}$ bands, allowing us to compute their colors. The photometry of the point sources in NGC 147 and NGC 185 is given in Table 2 and 3, respectively.

The flux densities within each of the *Spitzer*’s imager/photometer bandpass of a sample of Galactic AGB and K Giant star templates were determined using ISAP (ISO Spectral Analysis Package Version 2.0)³. As illustrated in Figure 13 and 14, the majority of point sources in the central region of NGC 147 and NGC 185 have colors similar to those of AGB stars. However, a handful of K Giant stars are clearly identifiable in each field due to their much “bluer” $[8] - [24]$ and $[5.8] - [8]$ colors. For the K Giant classification in Table 2 and 3, we used the selection criteria of $[8] - [24] < 0.8$ and $[5.8] - [8] < 0.3$.

The foreground contamination at 5.8, 8, and $24\mu\text{m}$ from Galactic stars in the “Total” emission region (as defined in Table 4 and seen in Figure 15 and 16) of each dwarf galaxy was estimated using a control field located $7'$ away from each dwarf galaxy. For both dwarf galaxy, we estimated a Galactic contamination of about 20%, with the remaining 80% of the infrared point sources belonging to the galaxies themselves. This implies that we detected and resolved ~ 28 dusty AGBs in NGC 147 and 185, respectively.

³ISAP is available at <http://www.ipac.caltech.edu/iso/isap/isap.html>

5. Spectral Energy Distributions

We measured the IRAC 3.6, 4.5, 5.8, & $8\mu\text{m}$ and the MIPS 24, 70, & $160\mu\text{m}$ flux densities on the images in the spatially resolved regions common at all wavelengths, as depicted in Figure 15 and 16 and listed in Table 5 and 6. In the case of NGC 147, we were unable to detect significant dust emission at 70 and $160\mu\text{m}$. The values reported in Table 5 at these wavelengths are the 1σ sensitivity upper limits measured from the standard deviation maps. The flux uncertainty for each region includes the combined effect of the systematic errors due to the post processing of the images, plus that of the flux density calibration of the instruments (Fazio et al. 2004; Rieke et al. 2004). The flux uncertainty, therefore, was estimated by measuring the residual flux density away from the galaxy in the background subtracted images and adding an absolute flux calibration uncertainty of 10% for the IRAC and MIPS $24\mu\text{m}$ measurements, and of 20% for the MIPS 70 & $160\mu\text{m}$ flux densities. The IRAC flux densities are corrected (multiplied) by the effective aperture correction factor of 0.944 ($3.6\mu\text{m}$), 0.937 ($4.5\mu\text{m}$), 0.772 ($5.8\mu\text{m}$), and 0.737 ($8\mu\text{m}$) (Reach et al. 2005). The corrected flux densities and uncertainties are given in Table 5 and 6.

The stellar photospheric component of the diffuse emission coming from each galaxy itself must be removed before the analysis of the dust component. We conservatively assume that, in addition to the 2MASS J, H, and K bands, all the light in the 3.6 and 4.5 IRAC bands is photospheric in origin. The J, H, K, IRAC 3.6 and 4.5 filter response functions were convolved with a PEGASE stellar evolutionary synthesis (SES) models (Fioc & Rocca-Volmerange 1997) with an age of 1 Gyr and a metallicity of $[\text{Fe}/\text{H}] = -0.7$. The SES models were computed at a metallicity of -0.7 since it is the closest metallicity point in our SES model grids to the measured metallicity of both galaxies ($[\text{Fe}/\text{H}] = -1.2$ and -1.1 for NGC 185 and NGC 147, respectively; Mateo 1998; McConnachie et al. 2005). However, the broad band dust SED fitting is not sensitive to the chosen metallicity and model runs at the two neighboring grid points in our SES models yielded identical results. There is also no diagnostic power in the age assumed; the PEGASE models were used here only to estimate the stellar contribution to the Spitzer bands, as simple power laws cannot reproduce the J, H, K colors. Scalings were derived for each band individually and averaged together to get the final scaling for the photospheric component. In all cases, the J through $4.5\mu\text{m}$ flux densities are consistent with being completely stellar in origin. To estimate the photospheric contribution to the flux density at longer wavelengths, we convolved the relevant IRAC and MIPS bandpasses with the PEGASE model and subtracted the result from the observed flux density to yield an estimate for the total dust flux density. For the relative contributions of the diffuse photospheric emission to the observed flux densities for NGC 185, see Table 7. The age we use for the PEGASE models does not significantly alter the dust fits; indeed, PEGASE models between 0.001–10 Gyr result in very similar estimates for the stellar contamination

in the Spitzer bands, especially for $\lambda \geq 8\mu\text{m}$.

6. Mass of Dust and Gas using SED Fitting

We can determine dust masses by fitting the total dust emission SED. The SED was measured between 5.8 and $160\mu\text{m}$, using IRAC and MIPS data. We measure the flux densities in the spatially resolved regions common to all wavelengths, as depicted in Figure 15 and 16 and listed in Table 5 and 6.

Modeling the dust emission in the dwarf galaxies requires the specification of both a dust model and a source of heating in the form of the radiation field the grains are exposed to. Grains exposed to the radiation field will absorb energy and emit according to their size and composition. Larger grains will tend to achieve an equilibrium temperature while smaller grains will undergo stochastic temperature fluctuations (Draine & Li 2001; Misselt et al. 2001). The temperature a given grain achieves (and whether it reaches equilibrium) is determined by the shape and intensity of the radiation field. Once the emission spectrum of each grain in the dust model has been computed, the total dust emission spectrum can be computed and scaled to fit the observations, where the scaling depends only on the dust mass and the distance to the source. Clearly, specifying the dust model and radiation field introduces a large number of free parameters to the fitting procedure: dust size distributions, dust composition, radiation field shape and intensity (Draine & Li 2007). To reduce the number of free parameters in our fit, we fix the dust model by adopting the BARE-GR-S model of Zubko et al. (2004) while to determine the radiation field, we adopt the PEGASE SES models (Fioc & Rocca-Volmerange 1997). The Zubko et al. (2004) dust model consists of three components, polycyclic aromatic hydrocarbons (PAH), graphitic grains, and silicate grains. With these assumptions, we have four free parameters in our fit: 1) the shape of the radiation field; 2) the intensity of the radiation field; 3) the total dust mass; 4) the distance to the galaxy. We fix the distances at 675 and 616 Mpc for NGC 147 and NGC 185, respectively (McConnachie et al. 2005). The shape of the radiation field is set by the age of the PEGASE SES model. The intensity of the field is set by first normalizing the SES to have the same energy content as the local interstellar radiation field as defined by Mathis, Mezger & Panagia (1983). The intensity is then parametrized by a dimensionless scaling factor applied to the normalized SES model.

With the above assumptions, the fitting proceeds as follows. Since there is no analytic relation between the radiation field and the dust emission spectrum, we take the approach of computing a large grid of possible galaxy SEDs and select the best fit (in the χ^2 sense) to the observed SED from the set of model SEDs. To compute the grid of model SEDs, we

compute 60 PEGASE SES models with ages ranging from 0-10 Gyr. For each age, the model stellar SED is normalized to the Mathis, Mezger & Panagia (1983) local radiation field and 200 dimensionless scalings between 0.1 and 2000 are applied. For each of the resulting 12000 model radiation fields, the dust emission SED is computed from the Zubko et al. (2004) BARE-GR-S model following the prescription of e.g. Misselt et al. (2001), yielding the dust emission per unit dust mass. This dust SED is then fitted to the observed SED with the only free parameter being the dust mass. Fixing the dust model as we have done results in a fixed relationship between the relative masses in each dust component (PAH, graphite, and silicates). Ranges for each parameter were measured by constructing 68% confidence intervals in the three dimensional parameter space.

6.1. NGC 147

Since only upper limits are available at 70 and 160 μ m (see Table 5 and Figure 17), we have almost no constraints on the dust mass for NGC 147 from SED fitting. The fitting procedure outlined above results in two classes of solutions that are able to fit the 8 and 24 μ m observations while not violating the 70 and 160 μ m upper limits. The first class is characterized by a small mass (\lesssim few M_{\odot}) of warm dust, whereas the second class is characterized by a large mass ($\gtrsim 10^7 M_{\odot}$) of cold dust. The low mass class of solutions satisfy the upper limit requirements by keeping the peak of the dust emission shortward of $\sim 40\mu$ m whereas the cold, massive solutions shift the peak of dust emission well longward of 160 μ m. However, the stellar component can be well fitted by the PEGASE model and there is no indication of an infrared excess at 8 μ m in this galaxy.

The current data and our fitting procedure provide little diagnostic power with respect to the properties of the ISM in NGC 147. However, some general observations can be made. The cold, massive solutions are unrealistic given the upper limit of the HI mass of $3 \times 10^3 M_{\odot}$ (Young & Lo 1997). On the other hand, the warm low mass solutions with dust masses between a few tenths to $\lesssim 1 M_{\odot}$ are consistent with the upper limit of $4.1 \times 10^2 M_{\odot}$ derived by Temi et al. (2004) (see below). Additionally, taking a gas-to-dust mass ratio of 160 appropriate for the Zubko et al. (2004) BARE-GR-S dust model, the gas masses implied by the warm, low mass solutions are of the order of $10^2 M_{\odot}$, a factor of 10^2 less than the upper limit of $9.9 \times 10^3 M_{\odot}$ derived by Sage, Welch & Mitchell (1998). On the other hand, neither the Sage, Welch & Mitchell (1998) upper limit nor the gas masses implied by our low mass class of solutions, is consistent with the estimated return of gas from evolved stars to the ISM of $5.5 \times 10^5 M_{\odot}$ calculated using the prescription of Faber & Gallagher (1976) for a time of 5×10^8 yr.

Similarly to Temi et al. (2004), we can also compute an upper limit on the dust mass in this galaxy from the upper limit on the flux density at $160\mu\text{m}$ using the standard relation (Hildebrand 1983):

$$M_d = S_\nu D^2 / \kappa_d B_{\nu,T}, \quad (1)$$

where S_ν is the measured flux density at frequency ν , D is the distance to the galaxy of 675 kpc, κ_d is the grain mass absorption coefficient for which we assume a value of $1.2 \text{ m}^2 \text{ kg}^{-1}$ at $160\mu\text{m}$ (Li & Draine 2001), and $B_{\nu,T}$ is the Planck function. If the dust temperature is assumed to be $\sim 20\text{K}$, this upper limit on the dust mass is $4.5 \times 10^2 M_\odot$. This value is consistent with the upper limit of $4.1 \times 10^2 M_\odot$ (and a temperature of $\sim 20\text{K}$) derived by Temi et al. (2004) from ISOPHOT observations using their upper limit on the flux density at $170\mu\text{m}$ of 0.21 Jy. Using a gas-to-dust mass ratio of 160, we infer an upper limit of the gas mass for the “Total” region of $7.2 \times 10^4 M_\odot$. This value is a factor of ten more than the upper limit of $9.9 \times 10^3 M_\odot$ derived by Sage, Welch & Mitchell (1998). It is however a factor of ten less than the estimated return of gas from evolved stars to the ISM of $5.5 \times 10^5 M_\odot$ calculated using the prescription of Faber & Gallagher (1976) for a time of $5 \times 10^8 \text{ yr}$.

6.2. NGC 185

The best SED fits to the data for each region of NGC 185, which produce the dust masses given in Table 8 and 9, are shown in Figure 18. We measure a total dust mass for the “Total” region of $1.9 \times 10^3 M_\odot$. This estimate agrees with the value of $1.5 \times 10^3 M_\odot$ (at a temperature of 22 K) derived by Temi et al. (2004) from ISO observations. Using a gas-to-dust mass ratio of 160, we infer a gas mass for the “Total” region of $3.0 \times 10^5 M_\odot$. This value is also in agreement, within a factor of ~ 3 , with the value of $7.3 \times 10^5 M_\odot$ derived by Sage, Welch & Mitchell (1998) and the estimated return of gas from evolved stars to the ISM of $8.4 \times 10^5 M_\odot$ for an intermediate-age population $1 \times 10^9 \text{ yr}$ old.

Note that the best fit age for the “Total” region of 450_{-330}^{+550} differs greatly from the other regions, which are best fit assuming radiation fields produced by a very young population. This is probably due to the fact that the “Total” region contains emission from the entire galaxy and therefore more of an older population component.

Note also that no temperatures are reported in Table 9. The dust emission SED in our fitting procedure is the total emission from an ensemble of grains with a size distribution and hence a temperature distribution. Therefore, there is no single temperature for the ensemble, even for those components in thermal equilibrium (large graphitic and silicate grains). For

the stochastically heated components (PAH, small graphitic and silicate grains), speaking of a temperature even for a single grain size within the ensemble makes little sense. However, we can use a single-temperature fit to the 70 and 160 μ m data for the “Total” region to obtain an estimate for the dust temperature, assuming a modified black body emissivity function of the form:

$$F(\lambda) = \lambda^{-\beta} \frac{2hc^2\lambda^{-5}}{e^{hc/k\lambda T} - 1}. \quad (2)$$

Adopting an emissivity coefficient $\beta = 2$ (valid beyond 70 μ m; cf. Draine 2003), we estimate a temperature of ~ 17 K.

7. Spectral Properties of NGC 185’s Dust Clouds

7.1. Spectral Line Measurements

The remaining artifacts left in the IRS spectra, after extraction with SPICE, were cleaned using the interactive analysis and processing tool SMART⁴ designed for this purpose. The lines and features were then measured using PAHFIT⁵ (Smith et al. 2007) to analyze IRS low spectral resolution data in an automated way. Despite the low resolution, PAHFIT tries to fit important blended lines and features, for example [OIV] 25.890 μ m and [Fe II] 25.988 μ m, and provides useful diagnostics in the process, e.g. uncertainty on the fitted central wavelength. In those cases where these uncertainties were relatively large, a cross check was done manually using SMART. PAHFIT takes also into account the extinction arisen either from a simple fully-mixed or screen dust component, dominated by the silicate absorption bands at 9.7 and 18 microns. For our measurements we have chosen the most simple “screen dust extinction” approximation to implement a reasonable correction to the line fluxes. The measurements resulting from the PAHFIT are given in Table 10 and 11.

The wavelength coverage of the IRS spectra is nominally 5 to 40 μ m, although at longer wavelengths, in particular for relatively faint emission, some artifacts like fringing and noisy pixels, can affect the spectrum and therefore a reliable line identification is an issue. The useful wavelength (IRS Data Handbook Version 3.1, 2007) range is 5.2 to 37 μ m. This is relevant because some expected lines from photodissociation regions (PDR), like H₂ S(7)

⁴ <http://ssc.spitzer.caltech.edu/archanaly/contributed/smart/>

⁵ <http://tir.astro.utoledo.edu/jdsmith/pahfit.php>

5.51 μm and [Fe II] 35.35 and 35.78 μm fall near these edges and are not necessarily automatically fitted by PAHFIT. The fits are done at the native spectral resolution and the plotted spectra has been smoothed out using a boxcar filter with 3 pixels width, just slightly wider than a resolution element. The final spectra, along with identified lines and features, are shown in Figure 19. We notice that for a few emission lines the rest wavelength found by PAHFIT (Table 10) is off by more than 0.5 μm . This typically takes place in regions of the spectrum where the PAH emission is strong or near the edge of the spectrum (e.g. for the [Si II] 34.8 μm line).

7.2. Analysis of the Spectra

NGC 185 has been classified as a low luminosity Seyfert type 2 galaxy, based on its optical and radio properties (Panessa et al. 2006; Nagar et al. 2005), although the presence of a black hole as a possible driver of this activity has not been confirmed in X-ray observations (Brandt et al. 1997).

The analysis of the NGC 185 IRS spectra is relatively straightforward, and can be placed in a more global context, thanks to recent works on normal galaxies by the SINGs Legacy team (Draine et al. 2007; Roussel et al. 2007), or Seyfert galaxies (Buchanan et al. 2006), based on Spitzer data and IRS measurements. Although there are some difference in the IRS spectra between the three different observed positions, some trends are very similar: strong PAH emission, deep silicate absorption bands at ~ 9.7 and 18 μm , the presence of relative low excitation fine structure atomic emission lines, (except perhaps by the presence of [O IV] 25.9 μm) as well as that of the 0-0 S(0) and S(1) H₂ rotational lines. These features are clear indicators of the presence of dust and ultraviolet ionization from star formation activity. The spectra overall resemble that of a photodissociation region, and in this sense they look very much like that of some of object studied by Buchanan et al. (2006) in their sample of PAH-dominated Seyfert galaxies, e.g. NGC 3079. Note that NGC 3079, with its very red spectrum and strong PAH emission, shows a “bubble” at its center and that this bubble was probably created by winds released during a burst of star formation (Cecil et al. 2001).

PAHs provide an interesting diagnostic to classify galaxies emitting in the mid-infrared when they are compared to the silicate 9.7 μm absorption feature that enables one to distinguish between AGNs and starburst-dominated systems (Spoon et al. 2007). As pointed out before, the NGC 185 spectra show deep silicate absorption at 9.7 and 18 μm as well as strong 6.2 μm PAH emission. For our “North”, “Center” and “South” target positions, we measured the equivalent width (EW) of the 6.2 μm PAH emission feature (0.7 ± 0.2 , 0.4 ± 0.1

and 0.8 ± 0.2 , respectively) as well as the strength of the $9.7\mu\text{m}$ silicate feature (-1.0 ± 0.2 , -1.3 ± 0.3 and -2.6 ± 0.3 , respectively) and plotted the two quantities in the diagnostic diagram of Spoon et al. (2007; Figure 1). The flux in the $6.2\mu\text{m}$ PAH emission band is measured by integrating the flux above a spline interpolated local continuum from 5.95 to $6.55\mu\text{m}$. The EW of the PAH feature is then obtained by dividing the integrated PAH flux by the interpolated continuum flux density below the peak ($\sim 6.22\mu\text{m}$) of the PAH feature. The apparent strength of the $9.7\mu\text{m}$ silicate feature is inferred by adopting a local mid-infrared continuum and evaluating the ratio of observed flux density (f_{obs}) to continuum flux density (f_{cont}) at $9.7\mu\text{m}$, as defined in Spoon et al. (2007):

$$S_{sil} = \ln \frac{f_{obs}(9.7\mu\text{m})}{f_{cont}(9.7\mu\text{m})}. \quad (3)$$

The error bars were calculated from different measurements for slightly different fit to the continuum baseline. We did not apply any correction for possible water ice absorption features.

Based on these numbers, our spectra fall into the class 1C-2C (PAH-dominated spectra), 2B-2C (weaker PAH features than class 2C) and 2C. All spectra occupy part of the diagram that is populated mainly by starburst galaxies. The Seyfert galaxies and QSOs are generally classified as class 1A which are characterized by a nearly featureless hot dust continuum with a very weak silicate absorption feature at $9.7\mu\text{m}$. Therefore, based on its infrared properties, NGC 185 appears to be currently forming stars (with lifetimes of $\lesssim 20$ Myr). If this interpretation is correct, this relatively young stellar population has remained undetected until now, possibly due to the large extinction due to the large amount of dust in this galaxy.

If the PAH emission is indeed being excited by far-ultraviolet (FUV) radiation from young stars, then we can estimate the current star formation rate based on a relationship derived from recent surveys of galactic and extragalactic objects (Wu et al. 2005; Peeters 2004). Using the PAH emission at $7.7\mu\text{m}$ the star formation rate (SFR) can be estimated (Wu et al. 2005) to be,

$$\text{SFR}_{8\mu\text{m(dust)}} = \frac{\nu L_\nu[8\mu\text{m(dust)}]}{1.57 \times 10^9 L_\odot}, \quad (4)$$

where νL_ν is in L_\odot and the SFR is given in M_\odot/yr . Using the contribution of the three IRS target positions to the $7.7\mu\text{m}$ PAH feature computed from the “Total” $8\mu\text{m}$ flux density value in Table 6 (92 mJy), we estimate a current SFR $\sim 5 \times 10^{-11} M_\odot/\text{yr}$. Clearly this is a lower limit but not too far from what has been inferred before by Butler & Martinez-Delgado

(2005), i.e. a mean star formation density rate of at least $2.6 \times 10^{-9} \text{M}_{\odot} \text{ yr}^{-1} \text{ pc}^{-2}$ within the central $2'$ over 10^9 yr.

The H_2 0-0 S(0), 0-0 S(1), 0-0 S(2), and 0-0 S(3) pure rotational line emission arising from the PDR has been estimated by Kaufman, Wolfire & Hollenbach (2006) and depends on the PDR temperature, the hydrogen nucleus density n (in units of cm^{-3}) and the FUV radiation field strength G_0 (in units of $1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1}$, the local ISM strength of the diffuse radiation field; Habing 1968). We can compare our line ratios, for instance the ratio of the H_2 S(1) $17.03 \mu\text{m}$ and S(0) $28.22 \mu\text{m}$ lines, to the predicted line ratios of Kaufman, Wolfire & Hollenbach (2006). For the three observed positions (“North”, “Center” and “South”, respectively) our calculated ratios of S(1)/S(0) are 2.1, 3.6 and 2.4, corresponding to a FUV radiation field in the range $2.0 \leq \log(G_0) \leq 5.0$ and a hydrogen nucleus density of $2.6 \leq \log(n) \leq 5$. These values are therefore consistent with having the molecular gas inside the dust cloud being impinged by the FUV radiation field of a relatively young stellar population in NGC 185.

In the outer layers of PDRs ($A_V \leq 1$), one expects emission from the [Si II] $34.8 \mu\text{m}$ and [Fe II] $26 \mu\text{m}$ transitions (Kaufman, Wolfire & Hollenbach 2006). The “North” and “South” positions show clear signs of the [Si II] $34.8 \mu\text{m}$ line, and very likely [Fe II]. The presence of [O IV] $25.89 \mu\text{m}$ in Seyfert galaxies using low resolution IRS spectroscopy has been recently discussed and analyzed on a relatively large sample of objects (> 50 ; Meléndez et al. 2008). The point has been made that the possible blending of the [Fe II] emission line at $26 \mu\text{m}$ is an issue, in particular for the less energetic objects. Because of this we have left PAHFIT to carry out the deblending of these two lines automatically and have kept both entries in our measurements.

Archival observations (from January 2004) in the ultraviolet (UV) by the XMM-OM instrument strongly suggest recent star formation activity in NGC 185 (see Figure 20). The XMM-OM camera was used with the UVW1 filter ($2330 - 2950 \text{\AA}$) and therefore overlaps in wavelength coverage with the GALEX NUV channel ($1800 - 2750 \text{\AA}$). This means that the UVW1 image can be used equally well as a reliable tracer of star formation. The XMM-OM camera has a $17'$ field-of-view with an angular resolution in the UVW1 band comparable to that of the IRAC bands ($\text{FWHM} \sim 2''$) and a sensitivity that matches within a factor of two that of GALEX (Morrissey et al. 2005; Mason et al. 2001). Figure 20 shows a comparison of the XMM-OM UVW1 observation (left) with those of *Spitzer* at $8 \mu\text{m}$ (center) and $24 \mu\text{m}$ (right) covering the central two arcminutes of NGC 185. The grayscale is such that bright regions are dark and extincted regions white. The brightest sources in the UVW1 image have been subtracted to emphasize the diffuse UV emission although some subtraction residuals are still present. The “North” dust cloud, located $\sim 15''$ from the center, is quite

distinguishable in the UV, as well as a fainter bridge that connects it with the “South” dust cloud. The white contours in the *Spitzer* images correspond to that of the UV emission which is essentially found at the center of the galaxy and surrounded by the dust clouds. Our spectroscopic observations have been positioned over the dust cloud purposely, therefore the fact that strong PAH emission is detected at these positions suggests that *locally*, i.e. not too far from the clouds, there is a source of UV photons interacting with them. Nevertheless, it is certainly possible that UV light from other sources (e.g. planetary nebulae) could also contribute to the excitation. If this is the case, this would affect the star formation rate computed above based on the $8\mu\text{m}$ emission.

In Figure 21, we compare the average of the three IRS spectra with the measured and best fit SED for “NGC185Total”. The average spectrum was normalized to match the SED model in the $20 - 30\mu\text{m}$ wavelength region, where the stellar photometric contribution is the lowest. The figure also includes both the ISOCAM and ISOPHOT measurements of Xilouris et al. (2004) for comparison. The ISO data points are for measurements done at 4.5 , 6.7 , $15\mu\text{m}$ with ISOCAM, and at 60 , 90 , 170 and $200\mu\text{m}$ with ISOPHOT. There is remarkably good agreement between the best fit SED and the ISO data points even though the actual model fits were done using only the 2MASS and Spitzer data. The PAH features used in the model agree remarkably well with the data. At shorter wavelengths, the “NGC185Total” emission comes mainly from stars and therefore our average spectrum of the dust clouds falls below the model SED.

8. Summary

New IRAC, MIPS and IRS observations of NGC 147 and NGC 185 give a better assessment of the dust content and properties in these prototypical local dwarf galaxies. Spitzer’s high sensitivity and spatial resolution enable us for the first time to look directly into the detailed spatial structure and properties of the dust in these systems. The images of NGC 185 at 8 and 24 micron display a mixed morphology characterized by a shell-like diffuse emission region surrounding a central concentration of more intense infrared emission. The lower resolution images at longer wavelengths show the same spatial distribution within the central $50''$ but beyond this radius, the $160\mu\text{m}$ emission is more extended than that at 24 and $70\mu\text{m}$. On the other hand, the dwarf galaxy NGC 147 located only a small distance away from NGC 185 shows no significant infrared emission beyond 24 micron and its diffuse infrared emission is mainly stellar in origin.

For NGC 147, we obtain an upper limit for the dust mass of $4.5 \times 10^2 M_\odot$, a value consistent with the previous upper limit derived using ISO observations of this galaxy. For

NGC 185, the derived dust mass based on the best fit to the “Total” SED is $1.9 \times 10^3 M_\odot$, implying a gas mass of $3.0 \times 10^5 M_\odot$ (assuming a standard gas-to-dust mass ratio of 160). These values are in agreement with those previously estimated from infrared as well as CO and HI observations. The gas estimate is also consistent with the predicted mass return from dying stars, based on the last burst of star formation, 1×10^9 yr ago. Based on simply the 70 to $160 \mu\text{m}$ flux density ratio, the estimated temperature for the dust is $\sim 17\text{K}$. The fact that NGC 147 resembles more a “typical” dust and gas-free elliptical galaxy than NGC 185 (and NGC 205, for that matter, see Marleau et al. 2006) remains puzzling in the context of the possible binary system scenario.

In the case of NGC 185, we also presented full $5 - 38 \mu\text{m}$ low-resolution ($R \sim 100$) spectra of the main emission regions. The IRS spectra of NGC 185 show strong PAH emission, deep silicate absorption features and H_2 pure rotational line ratios consistent with having the dust and molecular gas inside the dust cloud being impinged by the far-ultraviolet radiation field of a relatively young stellar population. Although the current rate of star formation is quite low ($\sim 10^{-10} M_\odot/\text{yr}$), this suggests that the star formation history of NGC 185 is complex, perhaps as much as that of the more active NGC 205 (Monaco et al. 2009).

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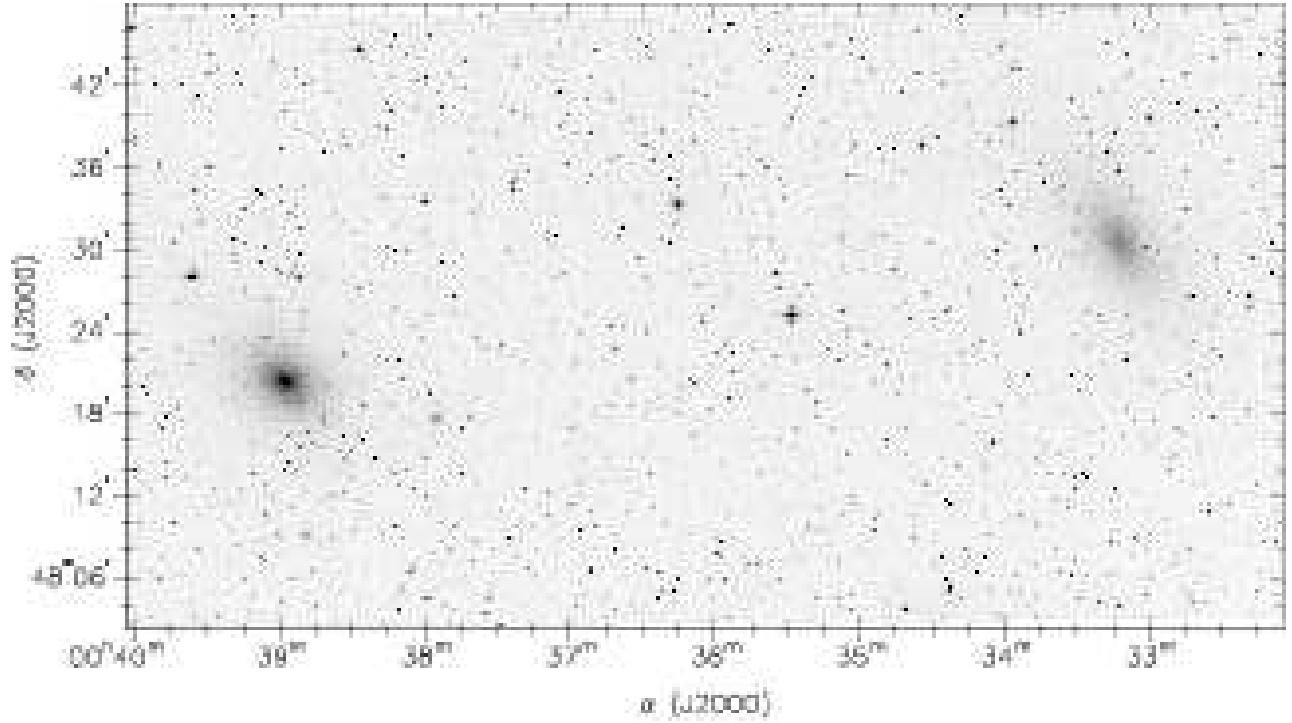


Fig. 1.— Digitized Sky Survey (DSS-2-red) image showing the location on the sky of the two satellite galaxies NGC 185 (*left*) and NGC 147 (*right*), with an angular separation of only roughly one degree (or ~ 11.2 kpc, assuming an average distance to these galaxies of ~ 645 Mpc).

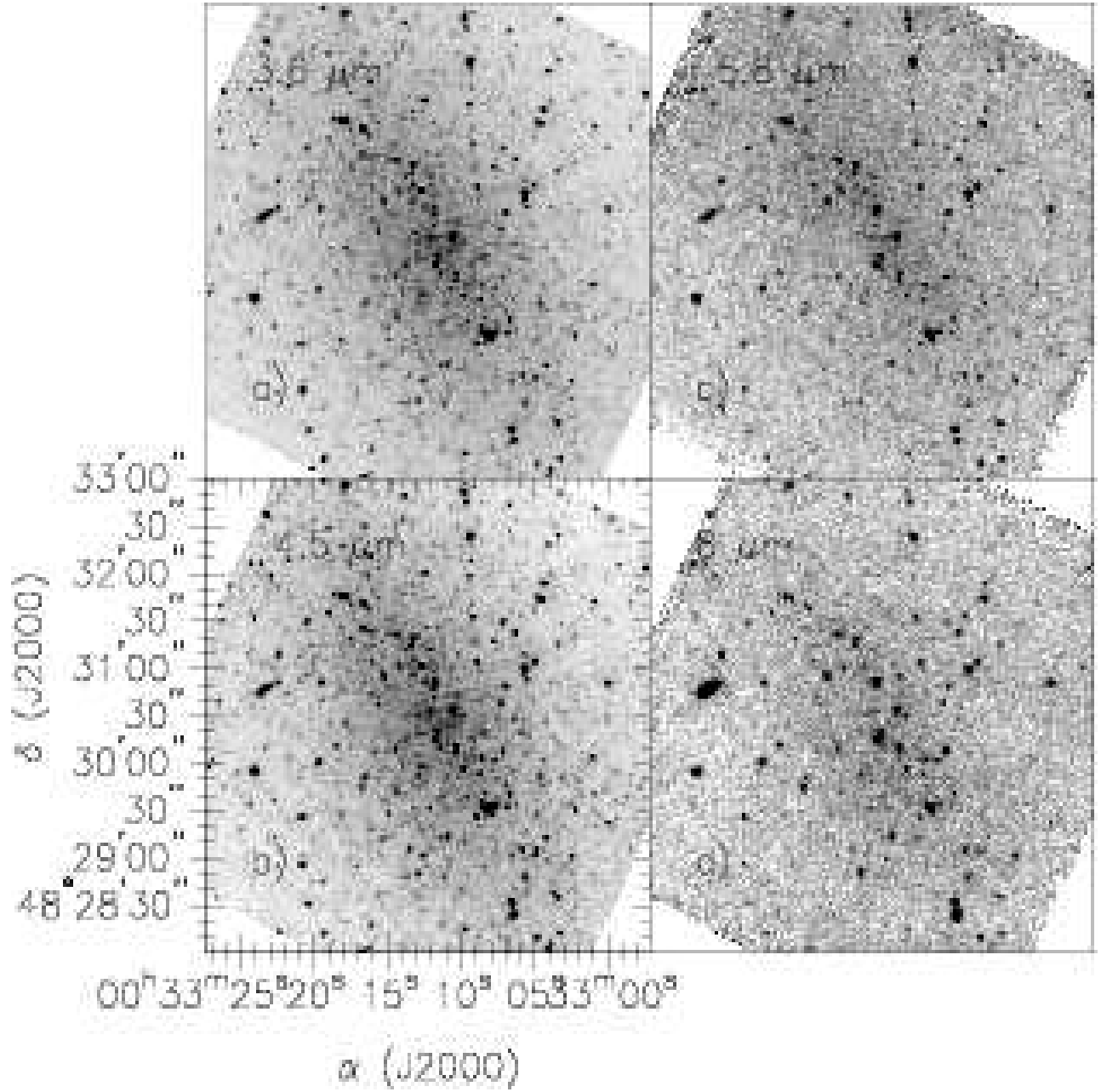


Fig. 2.— IRAC 3.6, 4.5, 5.8 & 8 μm images of NGC 147. The field-of-view (FOV) of each image is $5' \times 5'$ with N up and E to the left.

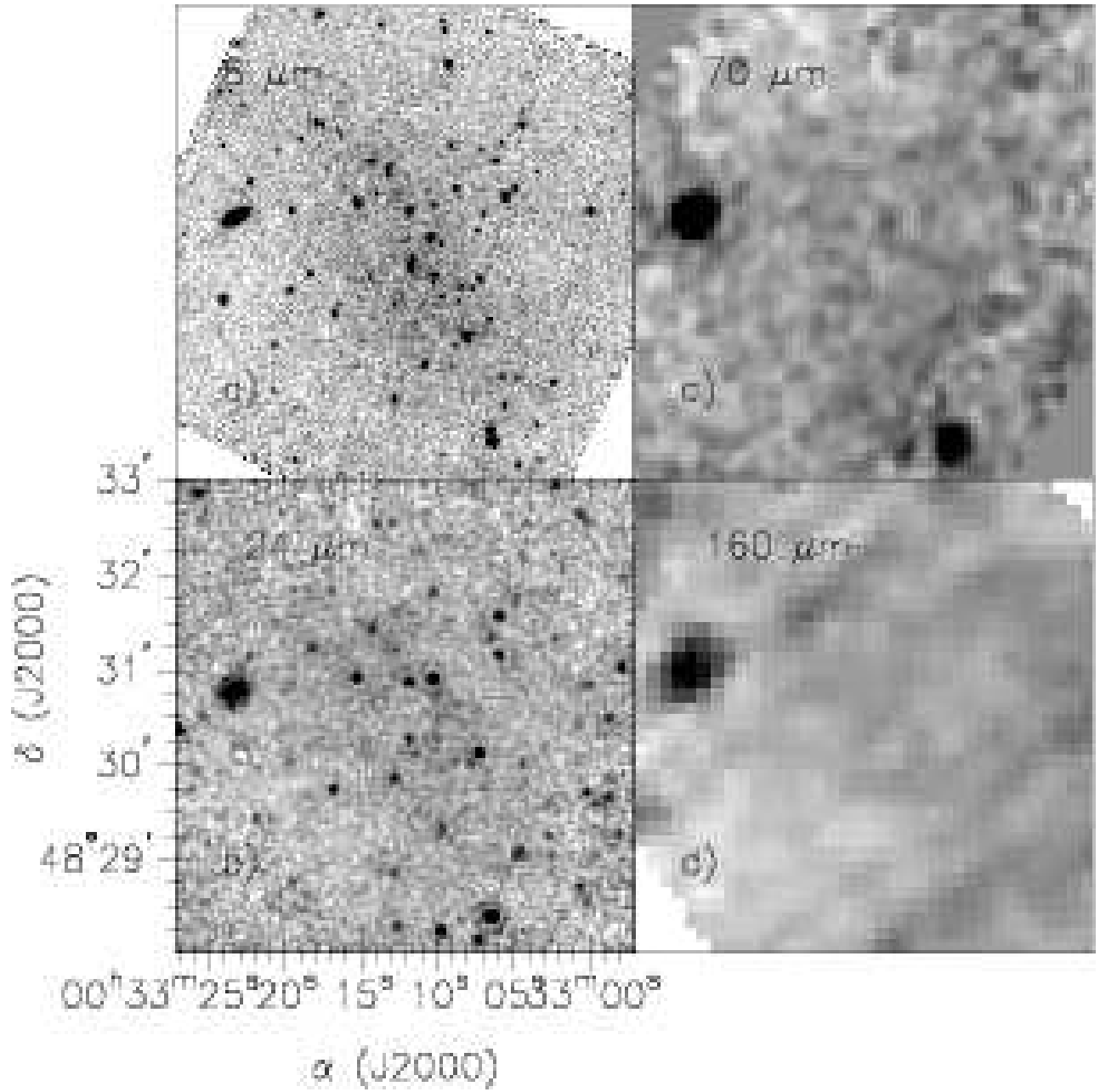


Fig. 3.— IRAC 8 μ m MIPS 24, 70 & 160 μ m images of NGC 147. The FOV of each image is 5' \times 5' with N up and E to the left.

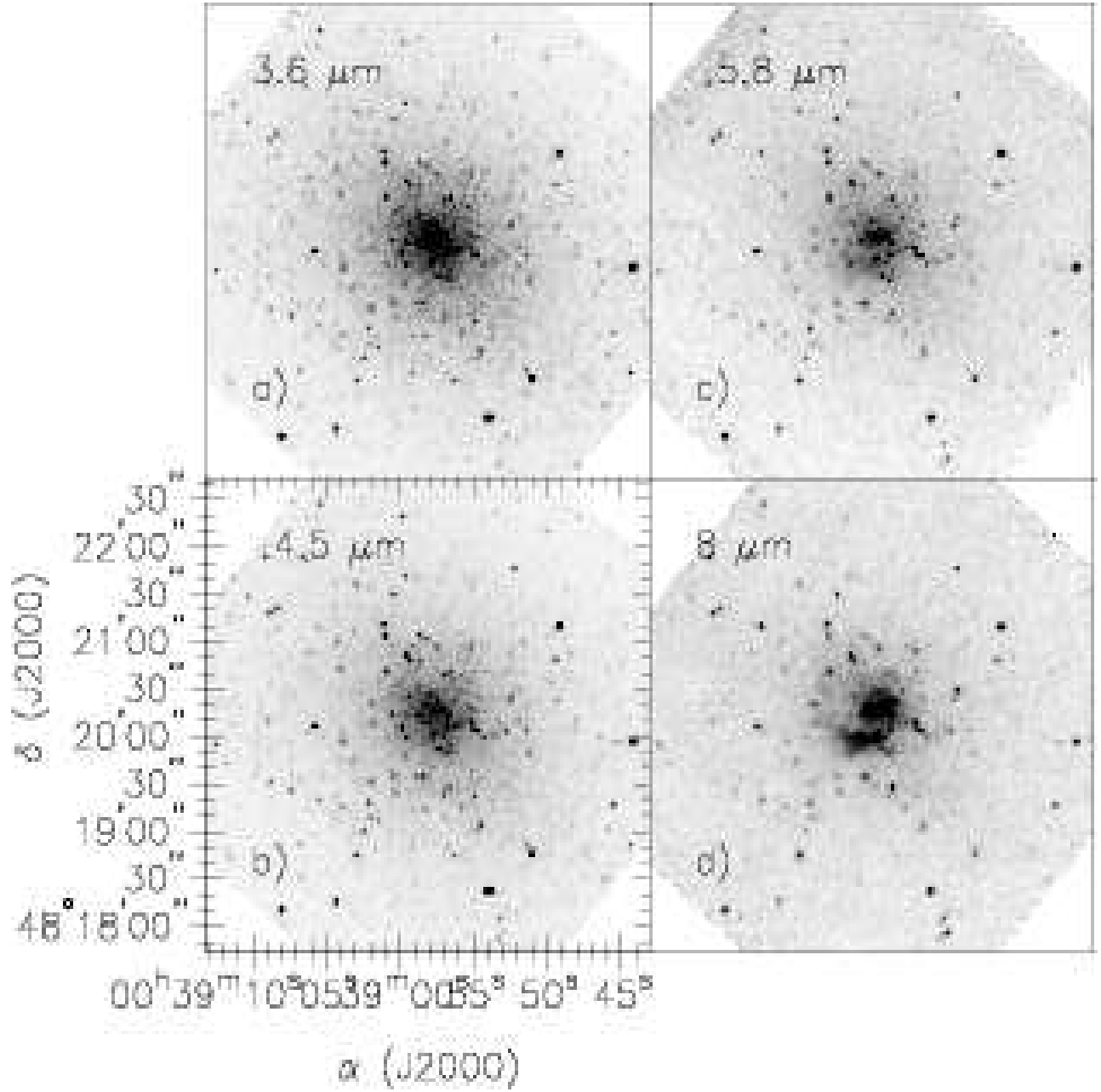


Fig. 4.— IRAC 3.6, 4.5, 5.8 & $8\mu\text{m}$ images of NGC 185. The FOV of each image is $5' \times 5'$ with N up and E to the left.

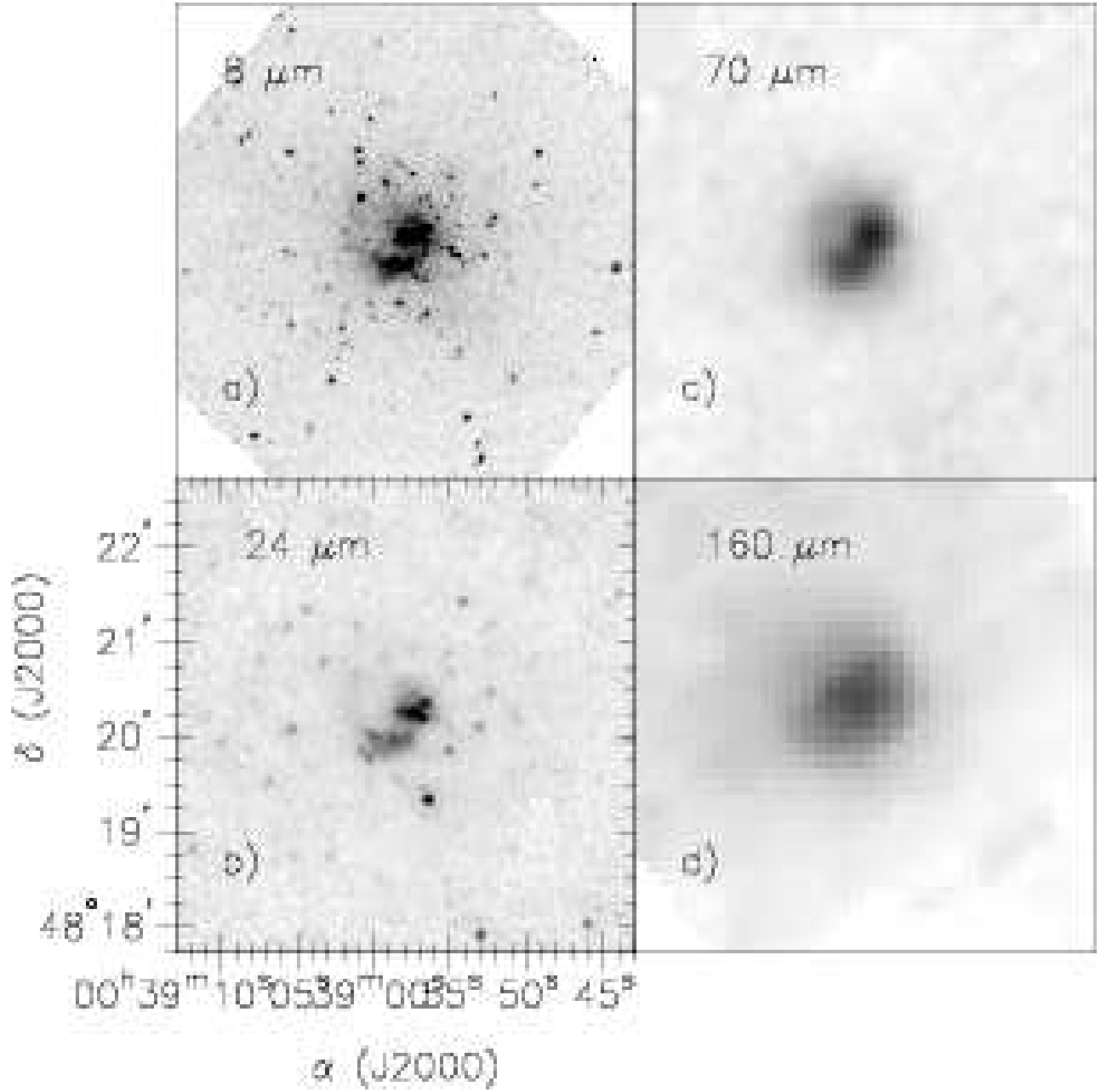


Fig. 5.— IRAC 8 μ m, MIPS 24, 70 & 160 μ m images of NGC 185. The FOV of each image is 5' \times 5' with N up and E to the left.

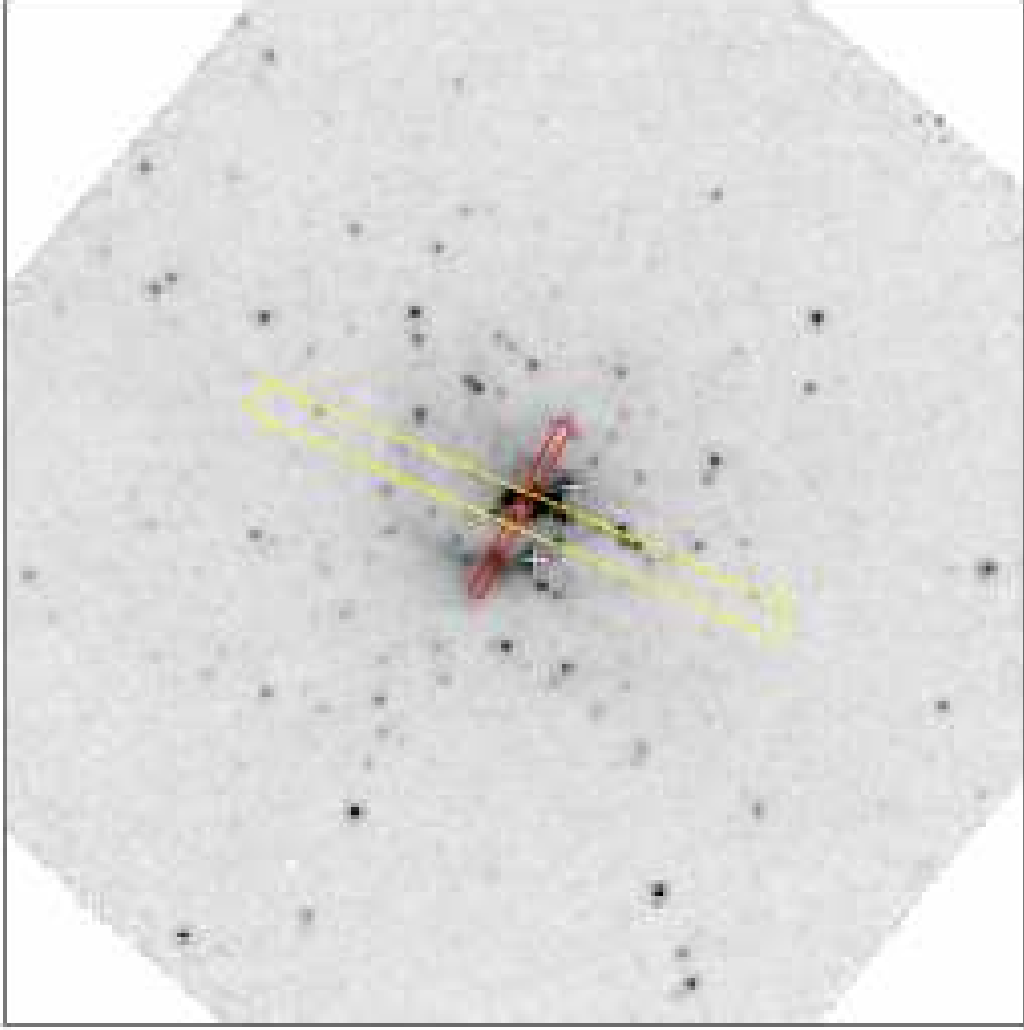


Fig. 6.— The three IRS target positions (*white crosses*), as given in Table 1, are shown overlayed on the IRAC $8\mu\text{m}$ image of NGC 185. The image is $5'$ on a side, with N up and E to the left. The IRS Short-Low (SL, *red*) and Long-Low (LL, *yellow*) slits are also displayed on the same image for one of the target position (NGC185IRSCenter).

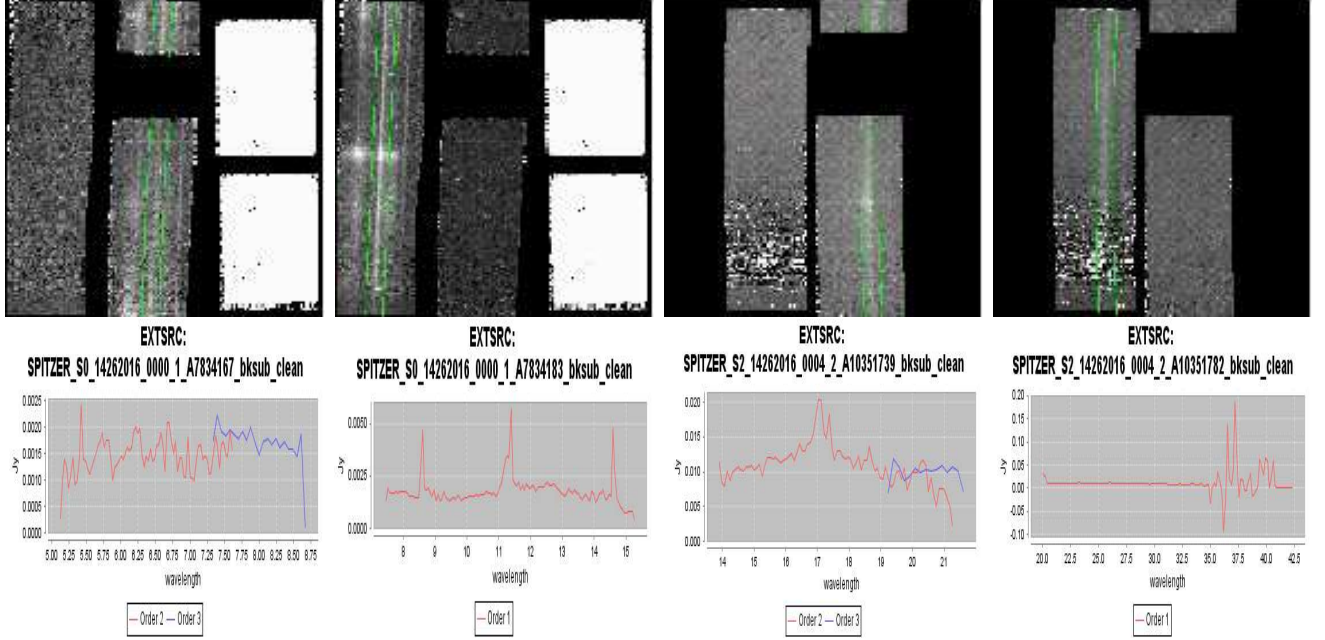


Fig. 7.— *Top*: Example of the spectral images taken at the “NGC185IRSNorth” (see Table 1) target position for, *from left to right*: the SL 2nd order, SL 1st order, LL 2nd order and LL 1st order. The *green lines* shows the region of extraction. *Bottom*: Extracted spectra corresponding to the spectral images shown at the top.



Fig. 8.— Three-color image of NGC 147 as seen by IRAC at 3.6 (blue), 5.8 (green) and 8 μm (red). The image shows that little dust emission is present in this galaxy and that only a diffuse stellar component is seen at shorter wavelength over a 5' square region, with N up and E to the left.



Fig. 9.— Three-color image of NGC 185 as seen by IRAC at 3.6 (blue), 5.8 (green) and 8 μm (red). The image emphasizes the dust clouds distribution seen at longer wavelengths over a 5' square region, with N up and E to the left.

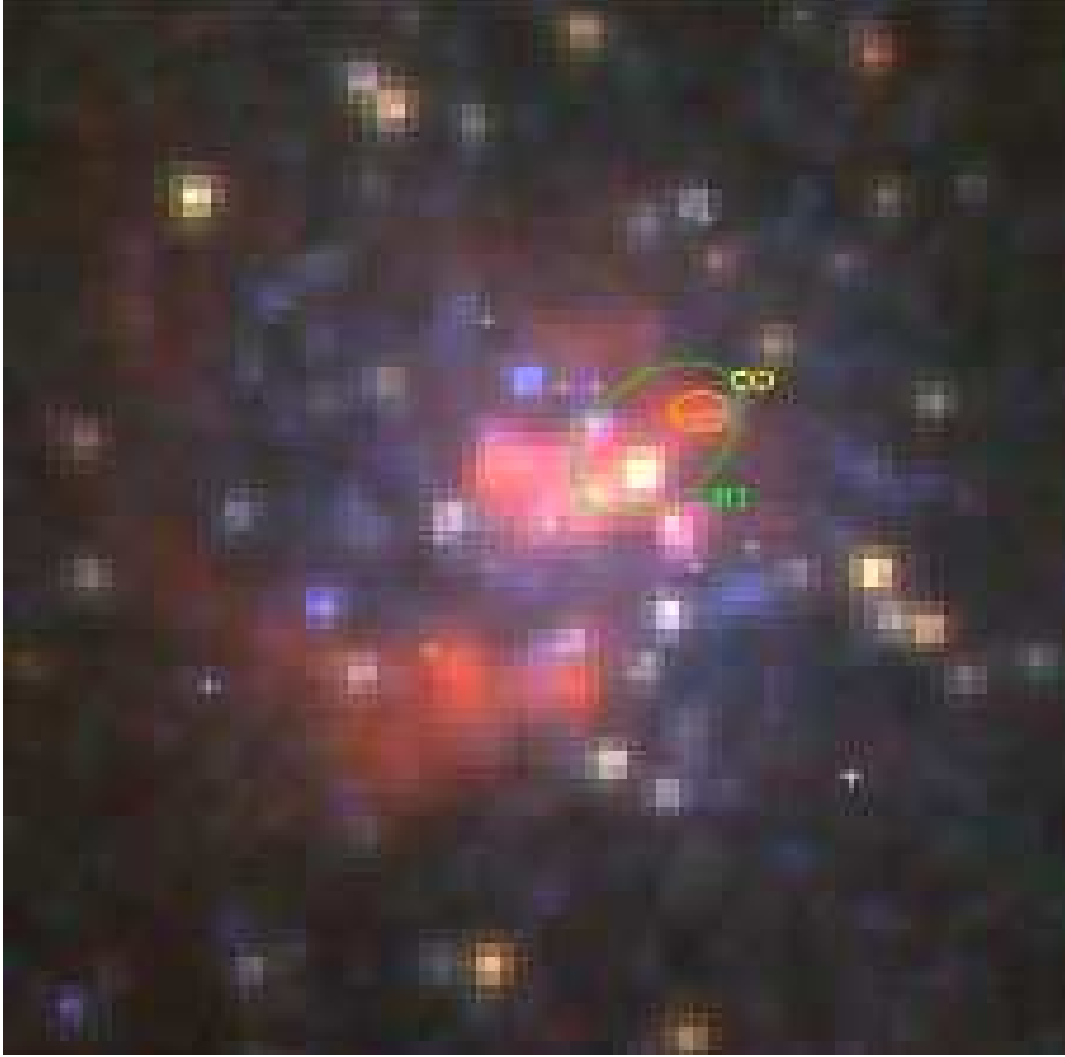


Fig. 10.— First main peak of each of the CO (*yellow contour*) and HI emission (*green contour*) (Young 2001) overlaid on the IRAC three-color image of NGC 185. The white plus signs indicate the locations of “Baade’s blue stars,” fifteen bright blue objects with a minimum age of 100 Myr originally reported by Baade (1951) and studied in more detail by Lee, Freedman, & Madore (1993) and Martnez-Delgado, Aparicio & Gallart (1999). The image covers a $1' 30''$ square region centered on NGC 185, with N up and E to the left.



Fig. 11.— Three-color image of NGC 185 as seen by MIPS at 24 (*blue*), 70 (*green*) and $160\mu\text{m}$ (*red*). The image shows that emission coming from the cold dust (*red*) is more extended than the one coming from other dust temperature and size components. The FOV of this image is $5' \times 5'$ with N up and E to the left.

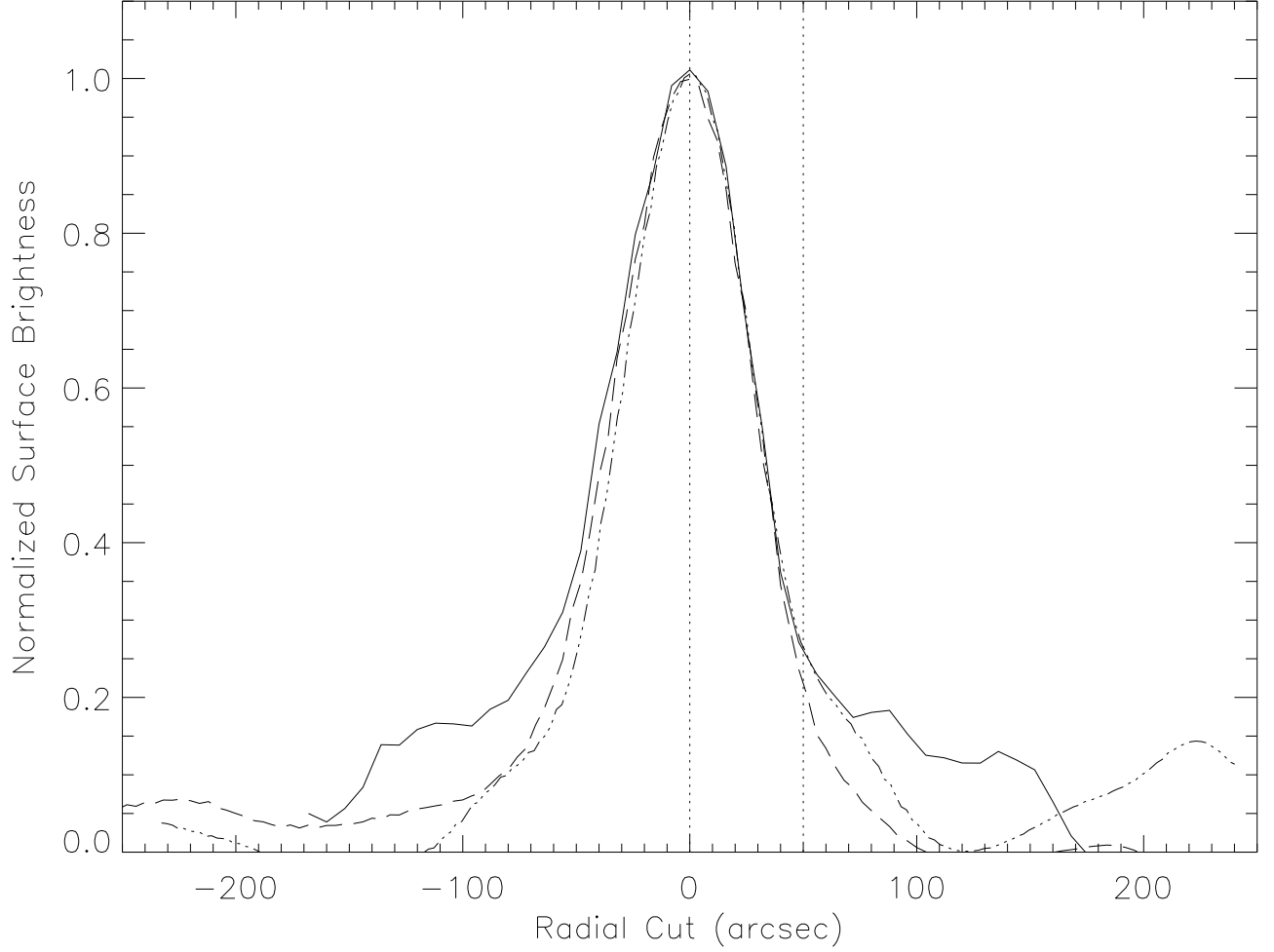


Fig. 12.— Comparison of the surface brightness radial profiles of NGC 185 in the three MIPS bands: $160\mu\text{m}$ (*solid line*), $70\mu\text{m}$ (*dashed line*) and $24\mu\text{m}$ (*dash-dotted line*). The three bands show similar profiles within the central $50''$ (*dotted line*) but beyond this radius, the $160\mu\text{m}$ emission is more extended than that at 24 and $70\mu\text{m}$.

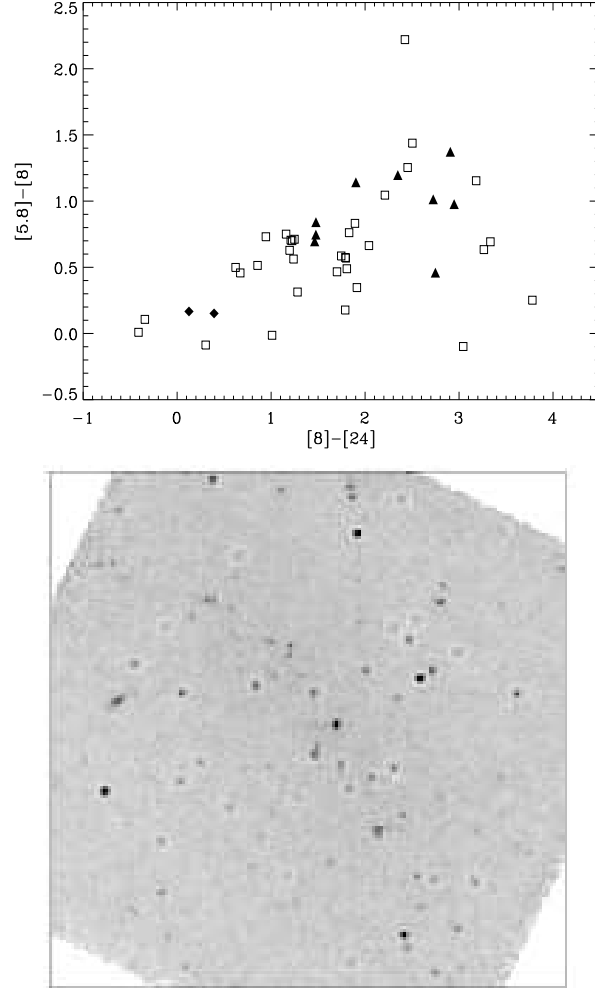


Fig. 13.— *Top*: Color-color diagram of a sample of K Giant stars (*filled diamonds*), AGB stellar templates (*filled triangles*), and the point sources extracted in the field of NGC 147 observe with IRAC and MIPS (*open squares*). *Bottom*: The point sources shown in the top figure, overlaid on the $5.8\mu\text{m}$ IRAC image of size $5' \times 5'$ with N up and E to the left. The AGBs and K Giants, as classified in Table 2, are identified with *squares* and *circles*, respectively.

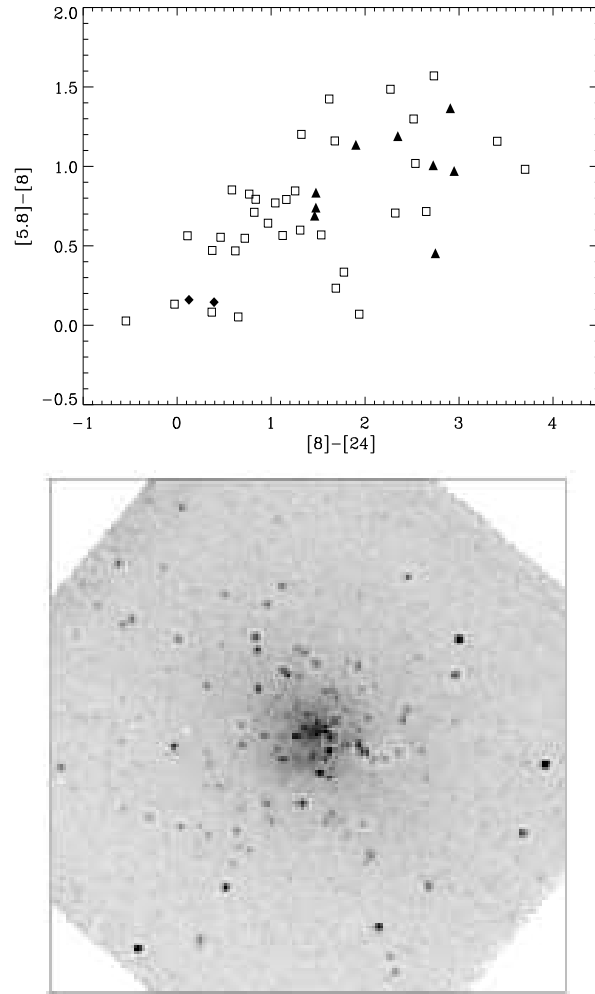


Fig. 14.— Same as Figure 13 but for NGC 185.

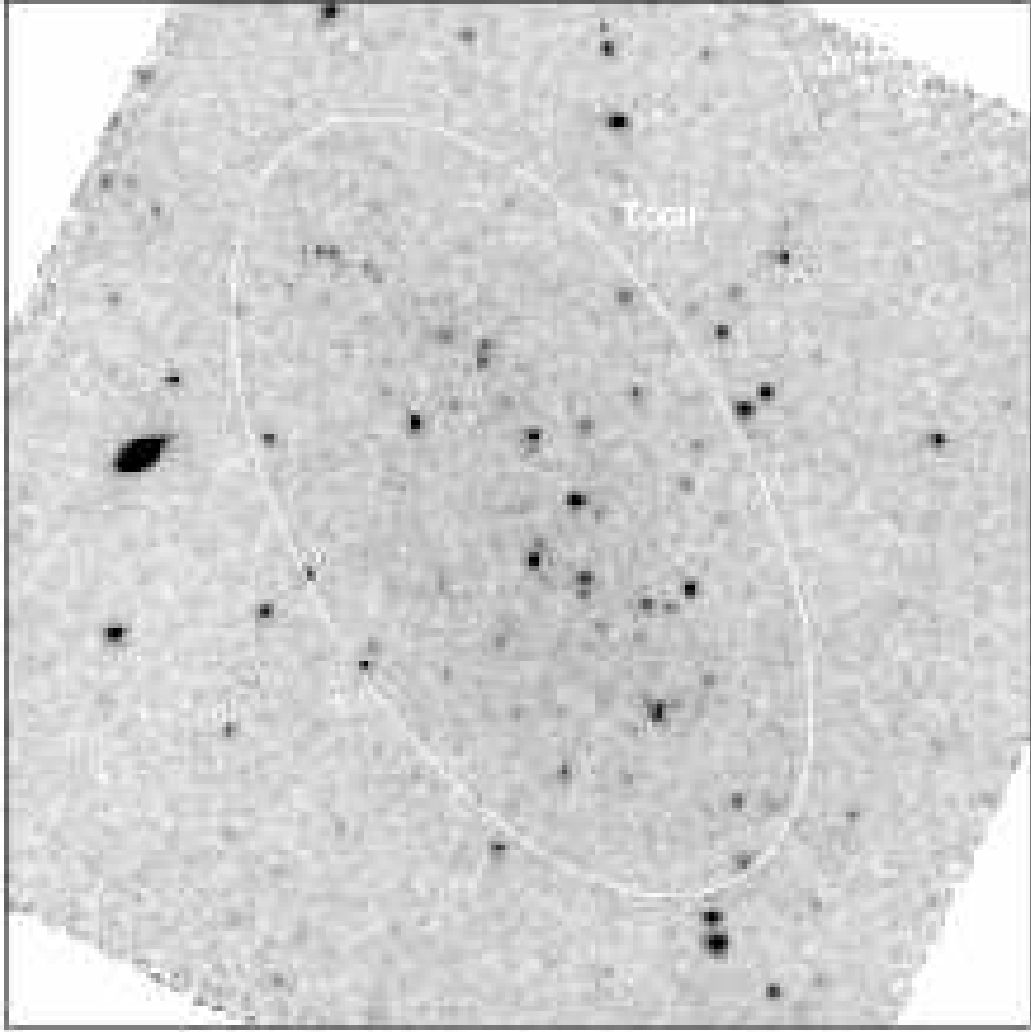


Fig. 15.— Emission region (as defined in Table 4), overlaid on the IRAC $8\mu\text{m}$ image of NGC 147. The FOV is $5' \times 5'$ with N up and E to the left.

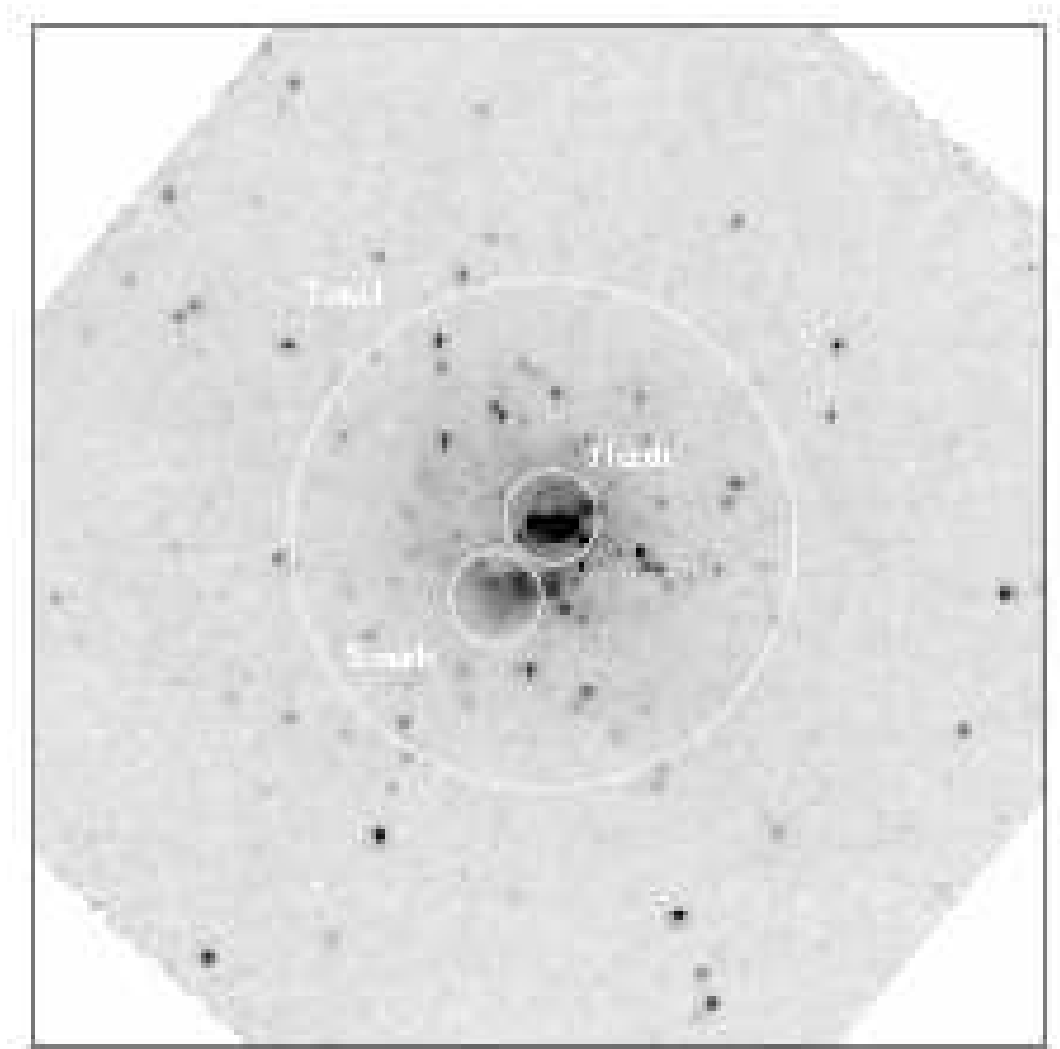


Fig. 16.— The two main emission regions, “North” and “South”, as well as the “Total” region (as defined in Table 4), overlaid on the IRAC $8\mu\text{m}$ image of NGC 185. The FOV is $5' \times 5'$ with N up and E to the left.

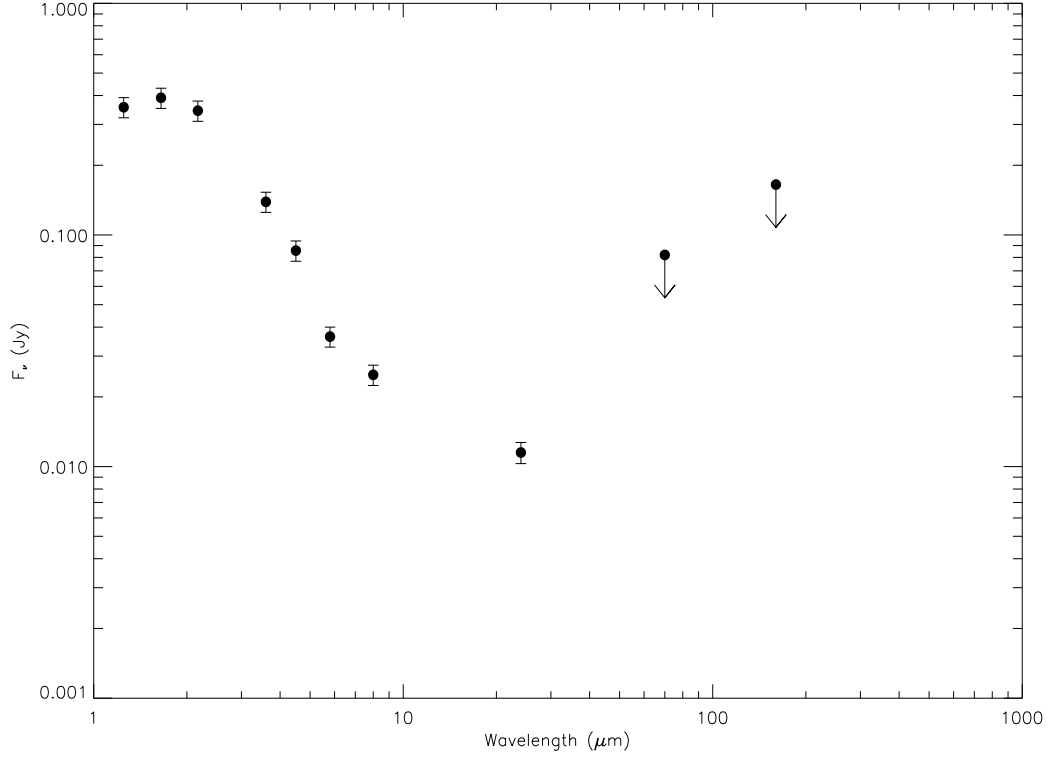


Fig. 17.— Infrared SED of “NGC147Total” region. The *solid* points are the data points as listed in Table 5. The *downward arrows* represent upper limits at 70 and 160 μm . Since only upper limits are available at 70 and 160 μm , we have almost no constraints on the dust mass for NGC 147 from SED fitting (therefore not shown here).

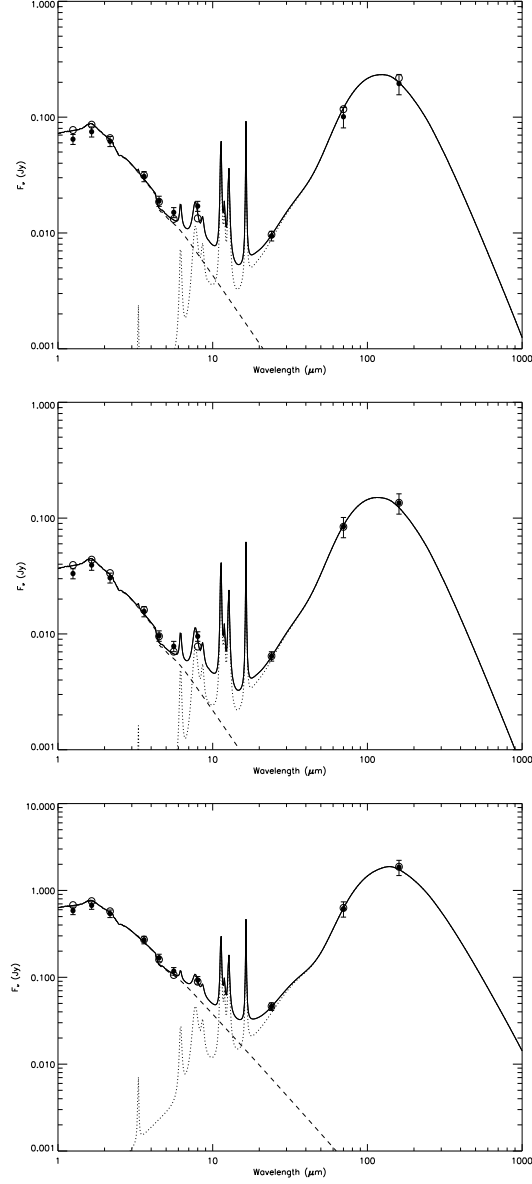


Fig. 18.— Infrared SED of the emission regions “NGC185North” (*top*), “NGC185South” (*center*) and “NGC185Total” (*bottom*). The *filled circles* are the data and the *open circles* are the model multiplied with the passband and integrated over wavelength. The *dashed line* is the stellar component (PEGASE model), the *dotted line* is the dust component (PAHs, graphites and silicates) and the *solid line* is the total of all components. Note that in the case of the “NGC185Total”, the upper limit of the y-axis is larger by a factor of ten.

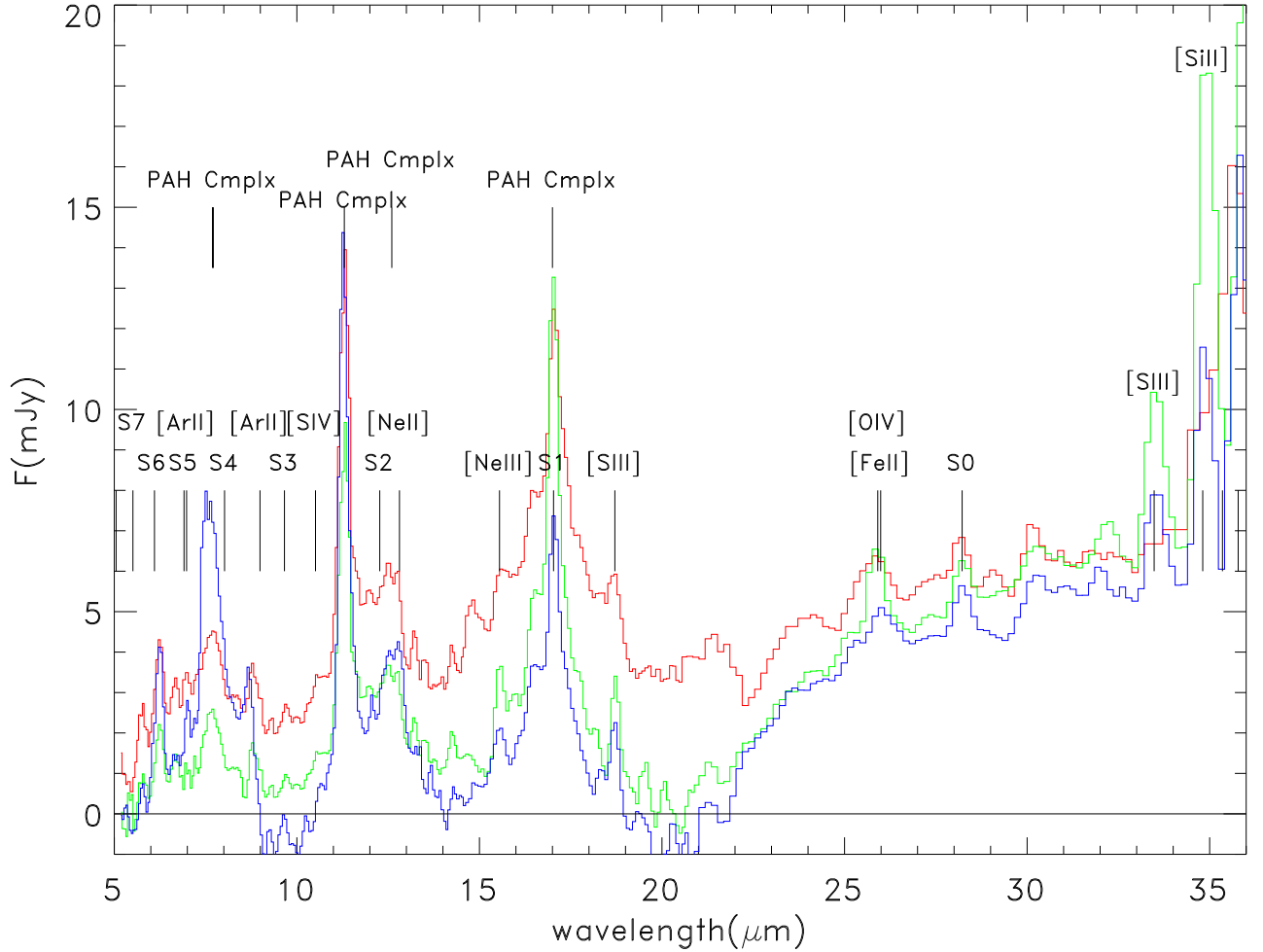


Fig. 19.— Extracted flux calibrated spectra for the “NGC185IRSNorth” (*red*), “NGC185IRSCenter” (*green*), and “NGC185IRSSouth” (*blue*) target positions. The main PAH complexes at 6.2, 7.7, 11.3, 12.7 and 17 μ m are indicated, as well as most of the measured emission lines, including those from molecular hydrogen. Deep silicate absorption features at ~ 9.7 and 18 μ m are clearly seen at the “NGC185IRSCenter” and “NGC185IRSSouth” positions. The spectral properties resemble overall those of a photodissociation region (except for the possible presence of [O IV] at 25.9 μ m) and are similar to those displayed by starburst galaxies or PAH-dominated Seyfert galaxies.

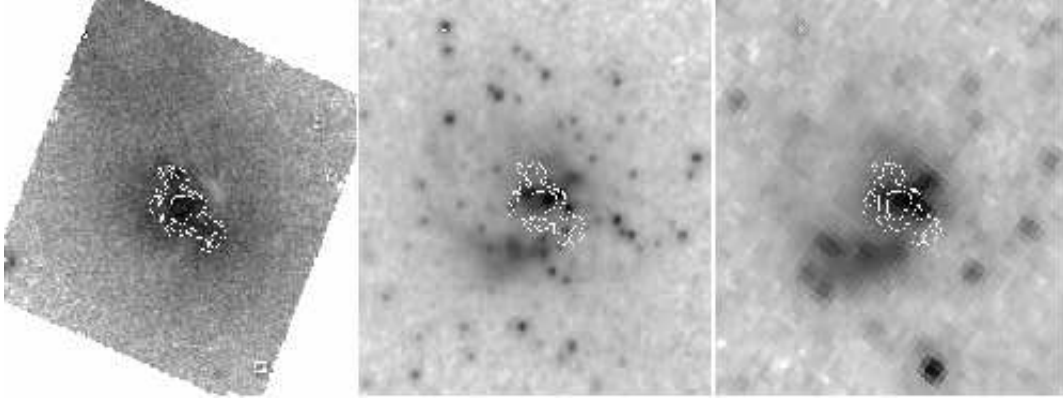


Fig. 20.— A comparison of the XMM-OM UVW1 observation (*left*) with those of *Spitzer* at $8\mu\text{m}$ (*center*) and $24\mu\text{m}$ (*right*) covering the central two arcminutes of NGC 185 with N up and E to the left. The grayscale is such that bright regions are dark and extincted regions are white; the contours are those of the UV diffuse emission.

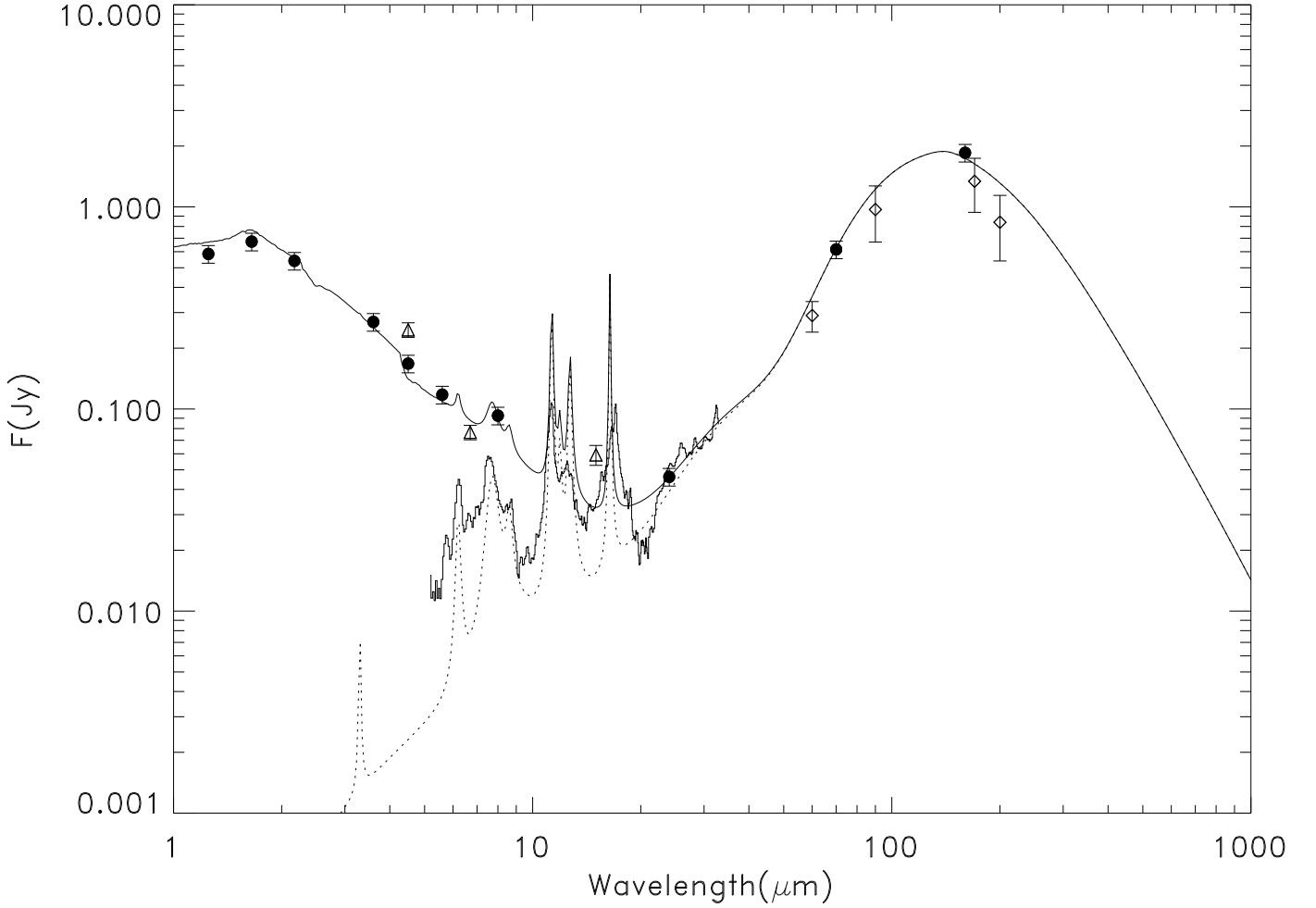


Fig. 21.— The average of the three IRS spectra overlayed on the model SED for “NGC185Total” (see Figure 18). The average spectrum was normalized to match the SED model in the $20 - 30\mu\text{m}$ wavelength region, where the stellar photometric contribution is the lowest. The *dotted line* is the PAHs component of the SED fit. The measurements shown on the plot are our photometry from IRAC and MIPS (*filled circles*) as well as the ISOCAM (*open triangles*) and ISOPHOT (*open diamonds*) data points.

TABLE 1
NGC 185 Spectral Extraction Positions

Position ^a	RA (J2000)	Dec (J2000)
	<i>h m s</i>	<i>° ′ ″</i>
NGC185IRSNorth	0 38 56.57	48 20 22.7
NGC185IRSCenter	0 38 57.97	48 20 14.6
NGC185IRSSouth	0 38 57.63	48 19 58.7
NGC185IRSSky	0 38 29.93	48 24 16.4

^aExtraction position as shown in Figure 6 (except for NGC185IRSSky which lies outside the field-of-view).

TABLE 2
Photometry of Infrared Point Sources in NGC 147

Source	Type ^a	RA (J2000)			Dec (J2000)			5.8 μ m	8.0 μ m	24.0 μ m
		<i>h</i>	<i>m</i>	<i>s</i>	<i>°</i>	<i>'</i>	<i>''</i>	Flux Density in mJy		
1	AGB	0	33	12.83	48	27	51.94	0.672	0.360	0.098
2	AGB	0	33	11.78	48	30	16.12	0.662	0.685	0.227
3	AGB	0	33	15.25	48	30	56.11	0.617	0.675	0.391
4	AGB	0	33	17.76	48	32	56.07	0.581	0.499	0.095
5	AGB	0	32	59.94	48	30	51.28	0.556	0.602	0.188
6	AGB	0	33	19.56	48	30	51.65	0.496	0.432	0.102
7	AGB	0	33	11.81	48	30	52.36	0.461	0.538	0.330
8	AGB	0	33	19.65	48	30	00.81	0.425	0.387	0.130
9	AGB	0	33	22.35	48	31	08.59	0.395	0.410	0.134
10	AGB	0	33	06.28	48	31	22.84	0.373	0.347	0.186
11	AGB	0	33	06.40	48	28	24.10	0.361	1.513	1.514
12	AGB	0	33	10.27	48	30	10.56	0.358	0.296	0.059
13	AGB	0	33	07.19	48	30	07.87	0.355	0.611	0.628
14	AGB	0	33	08.17	48	29	30.23	0.344	0.249	0.087
15	AGB	0	33	02.43	48	29	02.06	0.315	0.290	0.162
16	AGB	0	33	20.80	48	29	25.98	0.307	0.297	0.096
17	AGB	0	33	18.45	48	30	11.55	0.268	0.285	0.073
18	AGB	0	33	09.80	48	29	56.23	0.223	0.233	0.079
19	AGB	0	33	04.83	48	29	03.85	0.222	0.110	0.195
20	AGB	0	33	20.53	48	31	29.89	0.191	0.122	0.068
21	AGB	0	33	16.77	48	29	45.21	0.179	0.365	0.393
22	AGB	0	33	03.43	48	31	15.05	0.168	0.143	0.081
23	AGB	0	33	06.70	48	32	44.11	0.168	0.140	0.072
24	AGB	0	33	09.69	48	28	15.59	0.155	0.106	0.370
25	AGB	0	33	16.24	48	32	11.51	0.150	0.112	0.070
26	AGB	0	33	05.87	48	31	34.59	0.149	0.153	0.354
27	AGB	0	33	07.14	48	31	29.69	0.144	0.132	0.074
28	AGB	0	33	07.75	48	30	01.84	0.119	0.169	0.139
29	AGB	0	33	13.43	48	29	05.85	0.118	0.118	0.083
30	AGB	0	33	12.82	48	29	52.15	0.109	0.106	0.230
31	AGB	0	33	15.24	48	33	17.58	0.107	0.168	0.338
32	KGiant	0	33	24.09	48	29	54.60	1.666	0.997	0.078
33	KGiant	0	33	09.32	48	32	24.31	1.646	0.824	0.117
34	KGiant	0	33	05.60	48	31	00.34	1.567	0.857	0.063

^aClassification based on their infrared colors.

TABLE 3
Photometry of Infrared Point Sources in NGC 185

Source	Type ^a	RA (J2000)			Dec (J2000)			5.8 μ m	8.0 μ m	24.0 μ m
		<i>h</i>	<i>m</i>	<i>s</i>	<i>°</i>	<i>'</i>	<i>''</i>	Flux	Density in mJy	
1	AGB	0	39	02.86	48	18	45.59	1.003	1.198	0.220
2	AGB	0	39	01.10	48	21	11.52	0.838	0.879	0.201
3	AGB	0	38	58.39	48	19	34.44	0.694	0.809	0.176
4	AGB	0	38	45.53	48	19	16.92	0.616	0.564	0.067
5	AGB	0	38	56.75	48	20	12.55	0.540	1.156	1.004
6	AGB	0	39	08.34	48	21	21.79	0.534	0.449	0.068
7	AGB	0	39	09.11	48	21	54.37	0.532	0.480	0.100
8	AGB	0	38	49.45	48	20	49.24	0.528	0.520	0.136
9	AGB	0	38	52.24	48	21	46.49	0.521	0.437	0.083
10	AGB	0	38	54.91	48	20	04.72	0.513	0.472	0.208
11	AGB	0	39	05.58	48	21	10.26	0.480	0.791	0.287
12	AGB	0	39	00.42	48	21	30.66	0.476	0.432	0.071
13	AGB	0	38	59.50	48	20	51.81	0.463	0.438	0.157
14	AGB	0	38	57.58	48	20	56.21	0.459	0.545	0.186
15	AGB	0	38	52.78	48	20	03.94	0.437	0.484	0.136
16	AGB	0	38	52.27	48	20	29.22	0.389	0.787	0.375
17	AGB	0	39	05.50	48	19	20.62	0.389	0.440	0.102
18	AGB	0	38	52.98	48	17	56.38	0.354	0.819	1.089
19	AGB	0	38	53.63	48	20	01.15	0.294	0.218	0.120
20	AGB	0	38	54.26	48	19	59.38	0.289	0.265	0.080
21	AGB	0	38	55.09	48	20	53.72	0.278	0.441	0.222
22	AGB	0	39	01.93	48	20	20.29	0.277	0.313	0.098
23	AGB	0	39	07.27	48	19	26.24	0.262	0.177	0.090
24	AGB	0	38	54.86	48	19	22.76	0.253	0.147	0.094
25	AGB	0	38	56.44	48	20	22.33	0.240	0.380	0.940
26	AGB	0	38	54.95	48	20	41.44	0.225	0.235	0.214
27	AGB	0	39	16.96	48	19	36.79	0.192	0.346	0.377
28	AGB	0	39	11.55	48	21	12.41	0.130	0.137	0.169
29	AGB	0	38	53.18	48	20	07.76	0.107	0.144	0.468
30	AGB	0	39	07.94	48	20	23.90	0.079	0.110	0.122
31	KGiant	0	38	49.23	48	21	10.08	1.901	1.062	0.069
32	KGiant	0	38	44.23	48	19	57.22	1.754	1.080	0.113
33	KGiant	0	39	07.97	48	18	10.01	1.580	0.929	0.140
34	KGiant	0	38	41.00	48	21	05.91	1.280	0.732	0.143

^aClassification based on their infrared colors.

TABLE 4
NGC 147 and NGC 185 Emission Regions

Region ^a	RA (J2000)			Dec (J2000)			Area
	<i>h</i>	<i>m</i>	<i>s</i>	<i>°</i>	<i>'</i>	<i>''</i>	
NGC185North	0	38	57.73	48	20	19.7	0.17
NGC185South	0	38	59.39	48	19	55.7	0.17
NGC185Total	0	38	57.97	48	20	14.6	4.91
NGC147Total	0	33	12.12	48	30	31.5	7.26

^aCircular/elliptical aperture as shown in Figure 15 and 16.

TABLE 5
Photometry of Emission Regions in NGC 147

Wavelength	Total
μm	Flux Density in mJy
1.22	356 ± 36
1.65	391 ± 39
2.16	344 ± 34
3.6	139 ± 14
4.5	86 ± 9
5.8	51 ± 5
8	34 ± 3
24	21 ± 2
70	$82^{\text{a}} \pm 17$
160	$165^{\text{a}} \pm 32$

^a 1σ upper limit.

TABLE 6
Photometry of Emission Regions in NGC 185

Wavelength μm	North	South	Total
	Flux Density in mJy		
1.22	64 ± 6	33 ± 3	583 ± 58
1.65	75 ± 8	39 ± 4	671 ± 67
2.16	62 ± 6	30 ± 3	539 ± 54
3.6	31 ± 3	16 ± 2	269 ± 27
4.5	19 ± 2	10 ± 1	167 ± 17
5.8	15 ± 2	8 ± 1	117 ± 12
8	17 ± 2	10 ± 1	92 ± 9
24	9 ± 1	6 ± 1	46 ± 5
70	101 ± 20	84 ± 17	614 ± 123
160	194 ± 39	134 ± 27	1846 ± 369

TABLE 7
Stellar Photospheric and Dust Flux Density Contributions for NGC 185

Region	Wavelength μm	Total ^a mJy	Dust mJy	Stellar ^b	Dust Fraction
NGC185North	3.6	29.4	0.4	1.0	0.01
	4.5	16.2	0.5	0.54	0.03
	5.8	12.6	1.1	0.40	0.09
	8.0	13.4	6.8	0.22	0.51
	24.0	8.9	8.1	0.03	0.91
	70.0	106.8	106.7	0.00	1.00
	160.0	184.9	184.9	0.00	1.00
NGC185South	3.6	15.0	0.3	1.0	0.02
	4.5	8.4	0.4	0.54	0.05
	5.8	6.7	0.8	0.40	0.12
	8.0	8.6	5.2	0.23	0.61
	24.0	6.4	6.0	0.03	0.94
	70.0	86.8	86.7	0.00	1.00
	160.0	121.9	121.9	0.00	1.00
NGC185Total	3.6	255.2	1.3	1.0	0.01
	4.5	139.4	2.0	0.54	0.01
	5.8	104.8	4.1	0.40	0.04
	8.0	79.8	22.4	0.23	0.28
	24.0	45.1	38.2	0.03	0.85
	70.0	610.3	609.4	0.00	1.00
	160.0	1720.8	1720.6	0.00	1.00

^aThe measured flux density (photospheric plus dust contributions).

^bStellar flux density normalized with respect to that at $3.6\mu\text{m}$.

TABLE 8
Mass and Estimates from SED Fits for NGC 185

Cloud	Metallicity	Age Myr	Dust Mass M_{\odot}
NGC185North	-0.7	0^{+60}	$1.4^{+1.2}_{-0.6} \times 10^2$
NGC185South	-0.7	4^{+96}_{-4}	$7.7^{+5.9}_{-3.7} \times 10^1$
NGC185Total	-0.7	450^{+550}_{-330}	$1.9^{+1.9}_{-0.9} \times 10^3$

TABLE 9
Mass Estimates for Each Component for NGC 185

Region	PAH	Graphite	Silicate
NGC185North	$7.8^{+6.7}_{-3.9} \text{M}_{\odot}$	$4.11^{+3.52}_{-2.05} \times 10^1 \text{M}_{\odot}$	$9.91^{+7.81}_{-4.56} \times 10^1 \text{M}_{\odot}$
NGC185South	$4.3^{+3.3}_{-2.1} \text{M}_{\odot}$	$2.26^{+1.73}_{-1.09} \times 10^1 \text{M}_{\odot}$	$5.01^{+3.84}_{-2.41} \times 10^1 \text{M}_{\odot}$
NGC185Total	$1.05^{+1.05}_{-0.49} \times 10^2 \text{M}_{\odot}$	$5.58^{+5.58}_{-2.64} \times 10^2 \text{M}_{\odot}$	$1.236^{+1.236}_{-0.585} \times 10^3 \text{M}_{\odot}$

TABLE 10
Emission Lines in NGC 185 (Corrected for Extinction)

Line	Wavelength	NGC185IRSNorth	NGC185IRSCenter	NGC185IRSSouth
	μm	Intensity $10^{-10} \text{ W/m}^2/\text{sr}$	Intensity $10^{-10} \text{ W/m}^2/\text{sr}$	Intensity $10^{-10} \text{ W/m}^2/\text{sr}$
H ₂ S(6)	6.10	4.4 ± 1.2	2.6 ± 0.3	2.5 ± 0.4
H ₂ S(5)	6.91	...	3.7 ± 0.4	9.3 ± 0.4
[Ar II]	6.98	...	5.9 ± 0.3	...
H ₂ S(4)	8.02	27.3 ± 4.0^a	2.0 ± 0.3	3.1 ± 0.5
[Ar III]	8.99	7.4 ± 0.6	4.7 ± 0.1	...
H ₂ S(3)	9.66	4.7 ± 0.5	2.7 ± 0.1	0.3 ± 0.1
[S IV]	10.51	3.1 ± 0.5	2.5 ± 0.2	2.1 ± 0.1
H ₂ S(2)	12.27	2.8 ± 0.6	2.4 ± 0.3	3.8 ± 1.0
[Ne II]	12.81	2.9 ± 0.5	2.3 ± 0.3	5.3 ± 0.5
[Ne III]	15.55	5.4 ± 0.6	11.4 ± 0.3	4.7 ± 0.2
H ₂ S(1)	17.03	7.4 ± 1.3	31.3 ± 3.0^a	20.7 ± 2.0^a
[S III]	18.71	4.7 ± 0.4	7.3 ± 0.2	5.6 ± 0.2
[O IV]	25.91	3.6 ± 0.7	11.2 ± 0.7	6.5 ± 0.4
[Fe II]	25.99	3.3 ± 0.6	4.6 ± 0.6	5.9 ± 0.5
H ₂ S(0)	28.22	3.6 ± 0.4	8.7 ± 0.4	8.6 ± 0.6
[S III]	33.48	...	4.4 ± 0.5	2.8 ± 0.4
[Si II]	34.81	4.4 ± 0.6	12.6 ± 4.0^a	9.0 ± 3.0^a

^aarge uncertainty on the fitted rest wavelength.

TABLE 11
PAH Emission Features in NGC 185 (Corrected for Extinction)

Feature	Width ^a	NGC185IRSNorth	NGC185IRSCenter	NGC185IRSSouth
μm	μm	Intensity $10^{-9} \text{ W/m}^2/\text{sr}$	Intensity $10^{-9} \text{ W/m}^2/\text{sr}$	Intensity $10^{-9} \text{ W/m}^2/\text{sr}$
6.2	0.10	11.7 ± 0.7	4.8 ± 0.5	14.2 ± 1.0
7.7	0.60	23.8 ± 0.8	7.6 ± 1.0	35.3 ± 2.2
8.3	0.10	1.9 ± 0.8	...	3.3 ± 0.8
8.6	0.10	1.4 ± 0.7	...	5.8 ± 1.0
11.3	0.20	13.9 ± 1.2	11.8 ± 1.0	8.6 ± 1.5
12.0	0.20	3.8 ± 0.4	3.9 ± 0.7	2.9 ± 1.7
12.6	0.10	6.6 ± 1.4	5.0 ± 0.3	6.1 ± 0.3
13.6	0.20	...	1.1 ± 0.3	...
14.2	0.10	...	0.9 ± 0.3	...
16.4	0.10	0.9 ± 0.2	2.3 ± 0.4	2.4 ± 0.4
17.0	1.50	16.3 ± 0.4	10.0 ± 0.7	5.4 ± 0.5
17.4	0.10	0.2 ± 0.1	1.7 ± 0.3	1.4 ± 0.2

^aWidth of band of this feature.